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Review Paper

TEMPERATURE ESTIMATION METHOD OF ASPHALT PAVEMENT IN HUNGARY

UDC 625.85:666.9.015.67(439)

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Abstract. *Service life of the pavement can be predicted with proper temperature estimation of the pavement structure. Asphalt mixture displays a different modulus upon temperature change due to its viscoelasticity. The purpose of this study is to estimate such a temperature. Methodology in here includes one with the solution of heat conduction theory of the asphalt, and the other one statistical method. Results show that there is not a significant difference between the results made by two different methods. As a result of the model performance, the error range between the observed value and the predicted value is within the range suggested by other studies, so it is judged that the performance of the model is good. However, the prediction accuracy in the month with the highest and lowest temperatures per year was low. It seems that follow-up actions on this part will be necessary in the future. This study is expected to be used in various ways for road management in Hungary, and it is expected to be a basic study for the construction of road meteorological information system.*

Key words: *Asphalt mixture temperature, climatic load quantification, asphalt layer temperature estimation*

1. INTRODUCTION

Asphalt mixture shows a change in stiffness according to temperature, and thus shows behavior such as plastic deformation (e.g., rutting) and low-temperature crack in winter. Therefore, it is necessary to predict the temperature of the proper asphalt mixture to ensure the serviceability of the road. The internal temperature of the asphalt concrete pavement layer is determined in the form of temperature distribution by depth through a temperature prediction model based on the atmosphere temperature. Through the studies, it has been

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found that the factors that have the most influence on the asphalt pavement are air temperature and solar radiation.

There are two main ways to predict the temperature inside the asphalt. The first method is a prediction using regression analysis from actual data, and the second method is a prediction method based on heat conduction theory. Here, both methods are presented and the comparison between those two models is also presented.

In this study, a temperature prediction model for each depth of the asphalt pavement was prepared using the temperature distribution for each depth of the test road in Budapest, Hungary. The measurement devices were buried at 2 cm, 5 cm, and 10 cm from the pavement surface. The temperature of the asphalt pavement was recorded for a year and saved into a database.

The purpose of this study is to present basic data for the selection of appropriate asphalt for each region by establishing a temperature prediction model in the pavement according to temperature change, analyzing the change in the deformation coefficient according to temperature, and deriving the relationship between the atmospheric temperature and the deformation coefficient.

The algorithm for prediction of the internal temperature from the pavement surface temperature used finite difference method based on the heat conduction theory. By introducing and programming a numerical model to predict the internal temperature using the heat conduction theory, the measured data and the predicted data were compared and reviewed, and their applicability was verified.

2. BACKGROUND

In the United States and other countries, research on road surface temperature and temperature by pavement depth and model development are active.

The temperature of the pavement is determined by the external conditions such as insolation, atmospheric temperature, wind speed, precipitation, cloud coverage, water content of subgrade. The internal conditions by type of the binders also have an effect. Dickinson employed such external climatic conditions into the estimation of the asphaltic pavements' temperature [1]. Saas developed a Road Condition Model embedded in the automatic road temperature prediction system promoted by the Danish Meteorological Institute. The results of this study demonstrated that the sensitivity of temperature prediction showed a significant dependence on atmospheric meteorological data [2]. In Canada, a system called METRo was developed for research purposes at the request of the Canadian weather center. The advantage of this system is that it can use the weather and road temperature observation values collected from the road meteorological information system and the weather data predicted from the Canadian weather center's own model. At the same time, it can explain the accumulated state of water in the liquid or solid state on the road surface [3].

In terms of the heat balance, the temperature of the pavement surface is higher than the atmospheric temperature, so a temperature gradient toward the atmosphere occurs. The temperature change of the pavement surface due to solar radiation can be expressed in the form of Haversine curve [4]. Barber [5] assumed that the pavement could be modeled as a semi-infinite mass exposed to the effective air temperature. The author assumed that the maximum surface temperature can be expressed as a sinusoidal function, and the contribution of solar radiation to the average effective air temperature was quantified.

Solar energy from the sun at any time on the surface of the pavement is [4]

$$I(t) = \frac{2s}{t_1} \sin^2 \frac{\pi t}{t_1} \tag{1}$$

S: total insolation for a day (Wh/m^2), t_1: time (*h,* set as 0 at 1 hour before sunrise), *t*: time

At any time on the surface of the pavement, the convective energy between the surface of the pavement and the atmosphere is

$$E(t) = h_c[T_a(t) - T_s(t)] = h\Delta T(t) \tag{2}$$

h_c: coefficient of surface thermal transfer ($W / m^{2o}K$, T_a: air temperature (°*K*), T_S: surface temperature (^oK°)

Thus, the energy flux can be stated as,

$$\gamma I(t) - E(t) \tag{3}$$

γ: absorptivity of the surface for solar radiation

When calculating the surface temperature and the internal temperature of the pavement, it is convenient to start from the time when the temperature inside the pavement is the same as visually there is no temperature gradient inside the pavement.

A quadratic equation for the maximum and minimum pavement temperature which considers the latitude is suggested by [6] based on the energy balance.

$$q_{net} = q_s + q_a - q_c - q_k - q_r = 0 \tag{4}$$

q_s: direct solar radiation, q_a: atmospheric radiation, q_c: convection energy, q_k: conduction energy, q_r: radiation energy emitted from the surface

From the net energy balance of pavement structure, Solaimanian and Kennedy proposed the quadratic equation for the maximum pavement surface temperature prediction [6].

$$R_0 \cdot \alpha_1 \tau_a^{\frac{1}{\cos z}} \cos z + \varepsilon_a \sigma T_a^4 + h_c(T_s - T_a) - \frac{k}{x}(T_s - T_x) - \varepsilon\sigma T_s^4 = 0 \tag{5}$$

R_0: solar constant (1367 W/m^2), α_1: solar absorptivity (asphalt concrete: 0.85 ~ 0.93), τ_a: transmission coefficient (clear day =0.81, cloudy day = 0.62), *z*: Zenith angle, ε_a: coefficient of atmospheric radiation, σ: Stefan-Boltzman constant (5.67×10^{-8} $W/m^{2o}K^4$), *k*: thermal conductivity (1.36 W/m^oC), T_x: temperature at depth *x*.

The minimum surface temperature can be derived from equation (11) by eliminating the $q_s q_s$ term since the minimum temperature appears at the night without the sun.

$$\varepsilon_a \sigma T_a^4 + h_c(T_s - T_a) - \frac{k}{x}(T_s - T_x) - \varepsilon\sigma T_s^4 = 0 \tag{6}$$

Inside of the asphalt pavements, the temperature prediction is a transient problem. Straub et al. established a pavement temperature model for the atmospheric temperature and introduced an analysis method using the finite difference method. The temperature gradient at the time of calculation and the pavement temperature from the distribution of 24-hour temperature are analyzed [7].

3. MEASUREMENT

Temperature was measured in central Hungary. The sensor implanted on the test road collects the pavement's surface temperature and temperature at the certain depth (2, 5 and 10 cm) by 20 minutes of interval. The surface temperature distribution can be found in figure 1, and the monthly average temperature is described in table 1.

Table 1 Monthly Average Surface Temperature (°C)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
4.21	4.38	8.36	10.87	16.31	24.22	24.26	26.26	16.95	15.24	14.07	4.58

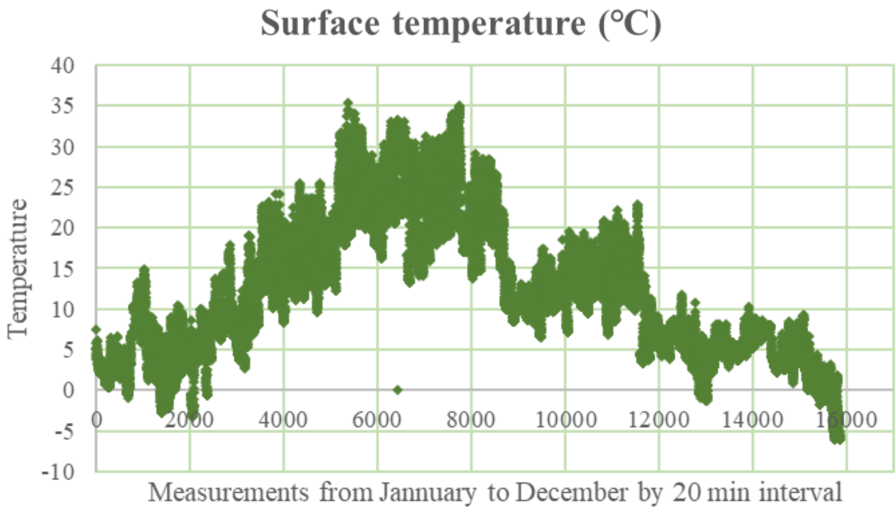

Fig. 1 Title of figure Surface temperature distribution of Budapest, Hungary

The surface temperature of Hungarian road does not exceed minimum -10 °C or maximum 40 °C. Based on this appearance, the temperature estimation model using statistical method uses 11 subdivisions [8] (following section 4.2).

4. TEMPERATURE ESTIMATION METHOD OF ASPHALT PAVEMENT IN HUNGARY

4.1. Pave-ut, a program for temperature estimation along the depth for Hungary

This program takes two main steps, which are first subroutine for surface temperature estimation and second subroutine for temperature estimation along the depth. For the validation, in this study only the 2, 5 and 10 cm depth points were chosen. The first subroutine is to find the solution of the heat-energy balance equation which describes heat transfer between surface and air. The second subroutine is to reflect the energy conduction of the asphalt mixture.

As Dickinson suggested the estimated values do not exceed ± 3 °C by the real value [1], the time steps and spatial discretization were done. The surface temperature of the pavement body can be obtained from the energy flux (equation 3), which is the difference between the absorbed heat and emitted heat and was solved by substituting environmental factors in Hungary.

For the prediction of the internal temperature change, the initial reference temperature of the pavement should be set as a boundary condition (equation 5,6). The other boundary condition is the temperature at the bottom of the asphalt concrete layer. Here in this study the base is assumed as the insulator, the temperature inside of the asphalt concrete layer does not transfer to the base layer.

Temperature prediction within the pavement depth is a transient problem. To predict the temperature change inside the pavement from the surface temperature change, the partial differential equation of heat conduction (equation 7 [9]) was solved by the finite difference method, which is one of the numerical analysis methods. In this study, Crank-Nicolson implicit method is used.

$$\rho C_v \frac{\partial T}{\partial t} - \nabla(kT) - S = 0 \tag{7}$$

ρ: density (2.24 t/m^3), C_v: specific heat, S: energy change

The solution by the finite difference method of this equation is developed as the following equations. To exploit the finite difference method, the space of the asphalt concrete layer is divided into the finite spatial element Δx and time Δt. The i is the location of the time node, and m is the location of the spatial node.

Temperature change with time on the surface (difference equation)

$$\gamma I(t) + h(T_a - T_o^i) + \kappa \frac{T_1^i - T_o^i}{\Delta x} = \rho C_v \frac{\Delta x}{2} \frac{T_o^{i+1} - T_o^i}{\Delta t} \tag{8}$$

ρ: density (2.24 t/m^3), κ: thermal conductivity (W / m^oK), h: specific heat (840 Ws/kg^oK)

And the temperature at the bottom of the asphalt layer estimation done with energy conservation is

$$\kappa \frac{T_1^i - T_o^i}{\Delta x} = \rho C_v \frac{\Delta x}{2} \frac{T_o^{i+1} - T_o^i}{\Delta t} \tag{9}$$

With the boundary conditions described in equation 14 and 15, the temperature inside of the pavement can be estimated.

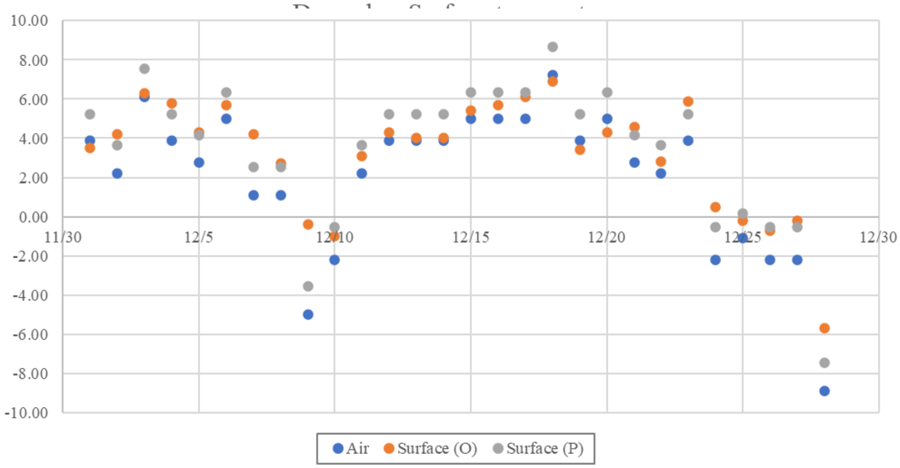

Fig. 1 Surface temperature distribution of December (O) and its prediction values (P)

Figure 2 shows the difference between the observed surface temperature (indexed as O) and predicted value (indexed as P). The surface temperature is always higher than the air temperature.

The material properties used for Hungarian climatic condition are shown below on the table 2. The input variables required for model performance were set as local values of Budapest.

Table 2 Thermal Equilibrium Equation Input Variables for Hungary condition

Index	Value
Solar absorptivity ($\alpha_1\alpha_1$)	0.9
Emissivity ($\varepsilon\varepsilon$)	0.9
Thermal conductivity (kk)	1.36 (W/m^oC)
Transmission coefficient	0.7
Thermal diffusivity ($\alpha\alpha$)	$\begin{cases} \text{day} & 0.7 \\ \text{night} & 0.89 \end{cases}$
Surface heat transfer coefficient	$\begin{cases} \text{day} & 19.8\ (W/m^oC) \\ \text{night} & 8.3\ (W/m^oC) \end{cases}$
Solar constant	1349 (W/m^2)

The finite difference method is a method of solving a differential equation as an algebraic differential equation under general boundary conditions, and the temperature of the center can be known [9]. The discretization of the space and time is done with the mesh size of $\Delta x = 0.2\,\Delta x = 0.2$ and $\Delta t = 0.2\,\Delta t = 0.2$. Here in this study the temperature distribution solution is done with the Crank-Nicolson implicit method (equation 10).

$$-\left(\frac{\alpha\Delta t}{\Delta x^2}\right)u_{i-1,j+1} + 2\left(\frac{\alpha\Delta t}{\Delta x^2}\right)u_{i,j+1} - \left(\frac{\alpha\Delta t}{\Delta x^2}\right)u_{i+1,j+1} = \left(\frac{\alpha\Delta t}{\Delta x^2}\right)u_{i-1,j} + 2\left(\frac{\alpha\Delta t}{\Delta x^2}\right)u_{i,j} + \left(\frac{\alpha\Delta t}{\Delta x^2}\right)u_{i+1,j} \quad (10)$$

Based on the finite different equation described above (equation 16), a program (Pave-ut) is built with Matlab. The temperature prediction results will be applied into the further structural analysis of pavement system as an input.

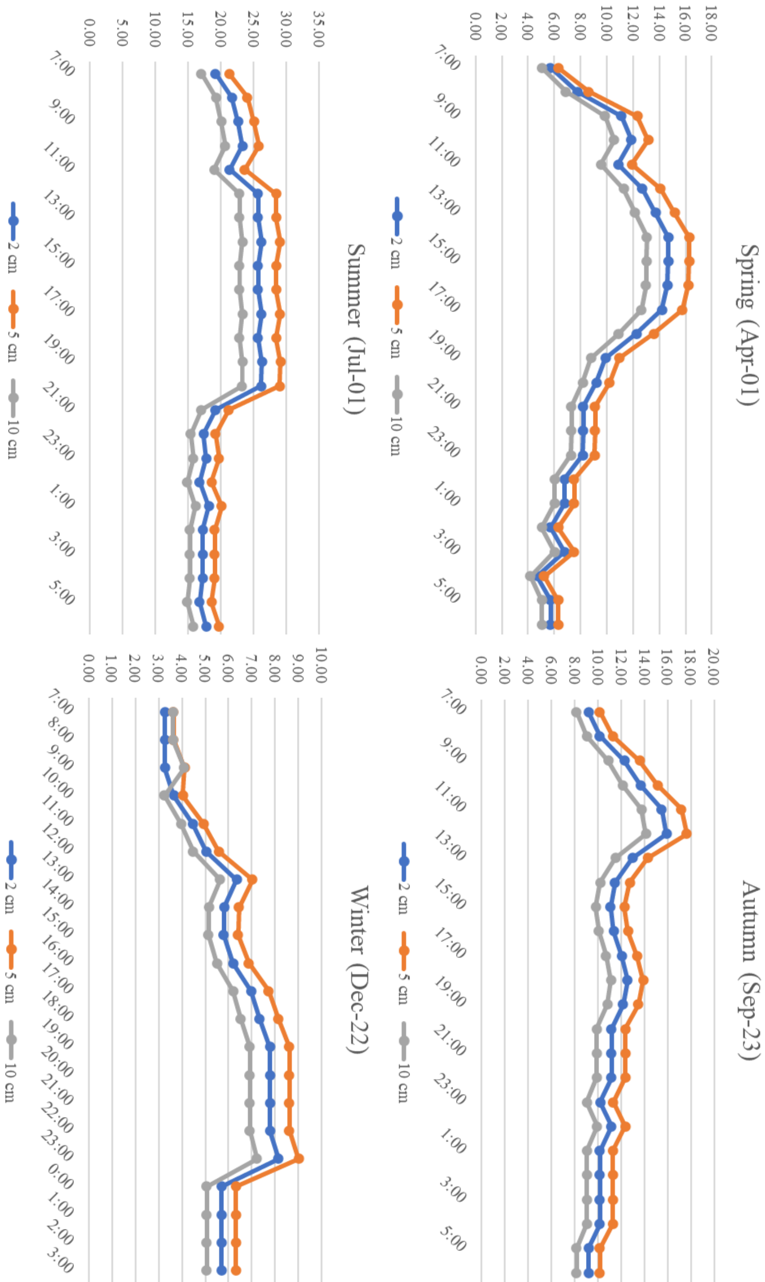

Fig. 2 Temperature gradients of Hungary

Figure 3 displays the temperature gradients of Hungary.

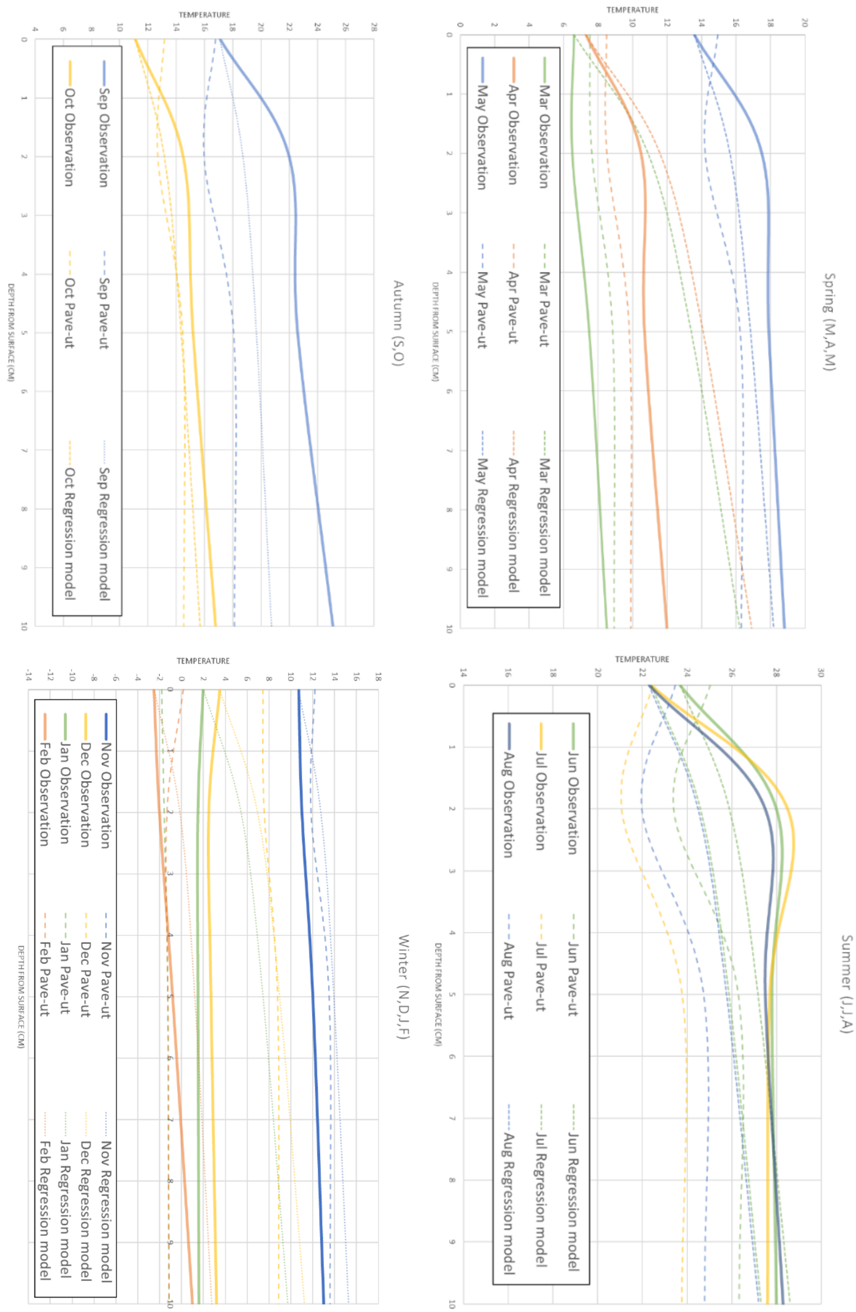

Fig. 3 Comparison of temperature gradient of two models (equation 15, equation 17)

4.2. Statistical Temperature Prediction Model for the Hungarian Road

There are two main streams to estimate the asphalt mixture's temperatures including the method based on heat transfer theory [4] and method based on historical data of that region [5]. The latter method uses the recorded observations and makes a regression model of it. The previous study of the authors used the second method, dealing with the statistical temperature model for Hungary [8]. This model is developed with the regression of the one year measured data. A measured data is subdivided into 11 subdivisions by the surface temperature, and the model coefficients are prepared for each of those. For the simplicity in the formation a square root function is used to represent the temperature distribution along the depth.

$$y = a \cdot \sqrt{x} + T_0 \qquad (11)$$

where, y is asphalt temperature (°C) at depth x (cm), T_0 is surface temperature (°C), and a is a parameter as a function of T_0 which is shown in table 4.

Table 3 Model coefficient α as a function of surface temperature

Surface Temp [°C]	≤0	≤5	≤10	≤15	≤20	≤25	≤30	≤35	≤40	≤45	<45
a [-]	1.669	2.446	3.044	1.449	1.154	1.553	1.086	-0.9228	-1.3158	-2.0504	-3.5124
R2	0.9969	0.9938	0.9773	0.9819	0.9949	0.8528	0.6896	0.7139	0.9162	0.8445	0.8948

The predicted values with the model (equation 11) are shown in Fig. 4. The model shows a good level of prediction accuracy (Fig. 4).

4.3. Comparison between the pave-ut model and statistical model

Figure 4 shows the results of specific months with two different models. Comparison is made based on data of 7 AM on the 1st of every month, however January is compared based on 15th due to the lack of observation data. The regression model (equation 11) predicts the internal temperature of the asphalt layer as the function of the surface temperature. Whereas the model introduced here (equation 10) uses the air temperature.

5. CONCLUSION

This study is prepared for the mechanistic-empirical design method of the Hungarian pavement system. The necessity of environmental load quantification cannot be too emphasized in modern pavement structural design. A new asphalt layer temperature model is introduced and a comparison with the former model using regression method is done in this study. From the result, a more accurate structural design and serviceability are expected.

Below are the findings of this study:

1) The result of the estimation shows an acceptable difference (within 3°C as stipulated in the literature).
2) The prediction accuracy in the month with the highest and lowest temperatures per year was low.

3) The regression model has a good level of internal temperature prediction with simple form as it is. However, since the model uses the surface temperature, it is difficult for general application without knowing the road surface temperature.
4) There is not a significant difference between the results calculated by two different methods.

The modeling of the pavement structure can be done better with properly estimated temperatures along the depth. This research provides a methodology for the estimation of the pavement layer's inside temperature by using the real historical data of Hungary. However, the measured data set used in this study is limited in one year and the input variables for heat conduction solution are found in the literature. Therefore, to improve the method to predict the pavement temperature more accurately, a long-term measurement of more than one year is required in a more systematic way and of the thermal characteristic variables of Hungary as well. The results of this study can be applicable as the input of the mechanistic-empirical design of the Hungarian pavement system.

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TEMPERATURNA METODA PROCENE ASFALTNIH KOLOVOZA U MAĐARSKOJ

Vek trajanja kolovoza može se predvideti pravilnom temperaturnom procenom kolovozne konstrukcije. Asfaltna mešavina pokazuje različite module pri promeni temperature zbog svoje viskoelastičnosti. Svrha ove studije je proceniti takvu temperaturu. Metodologija ovde uključuje jednu metodu sa rešenjem teorije toplotne provodljivosti asfalta, i drugu statističku metodu. Rezultati pokazuju da nema značajne razlike između rezultata dobijenih dvema različitim metodama. Kao rezultat performansi modela, raspon greške između uočene vrednosti i predviđene vrednosti je u rasponu koji su predložile druge studije, pa se procenjuje da je učinak modela dobar. Međutim, tačnost predviđanja u mesecu sa najvišim i najnižim temperaturama u godini bila je niska. Čini se da će ubuduće biti potrebne naknadne aktivnosti u tom delu. Očekuje se da će se ova studija na različite načine koristiti upravljanju putevima u Mađarskoj, a očekuje se da će biti i osnovna studija za izgradnju putnog meteorološkog informacionog sistema.

Ključne reči: *temperatura asfaltne mešavine, kvantifikacija klimatskog opterećenja, procena temperature asfaltnog sloja*

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Original Scientific Paper

AN ALTERNATIVE NUMERICAL MODEL FOR FIBER REINFORCED CONCRETE STRENGTH EVALUATION

UDC 666.972+677.53
620.173:691.32

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[2]Faculty of Civil Engineering and Architecture, University of Niš, Serbia

Abstract. *An alternative numerical model for fiber reinforced concrete (FRC) compressive and bending tensile strength determination is presented in this paper. Fibers are modeled explicitly by using the Extended Finite Element Method (XFEM). An alternative method for modeling the fiber-matrix interaction, without the need for additional subroutine definition, is proposed. The presented numerical model was evaluated by experimental tests and results are in good agreement. The model was developed for Simulia ABAQUS software, but the proposed modeling procedure is generally applicable. In the end, some possible model improvements and suggested applications are included.*

Key words: *fiber reinforced concrete, FRC, XFEM, discrete fiber model, fiber-matrix interaction, strength evaluation*

1. INTRODUCTION

1.1. Fiber reinforced concrete and its characteristics

Over the last several decades concrete has become the most widely used construction material in the world and it has been thoroughly studied thus far. One of the main shortcomings of concrete is its low strength when subjected to tension, and the most commonly used way for overcoming this shortcoming is reinforcing the concrete. This can be done in many ways, and the most commonly used one is through the application of steel rebar. However, numerous attempts have been made to find an alternative solution to this problem. One of these solutions is the microreinforced concrete (MRC),

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which can be MRC in a specific sense, or the fiber reinforced concrete. MRC in a specific sense is obtained when a concrete element is reinforced by some ductile and resilient strips near or on the surface of the element, e.g. [1,2].

Fiber reinforced concrete (FRC) is comprised of concrete matrix and some fibers that are more or less evenly, though randomly dispersed throughout the concrete matrix. One typical cross-section of a FRC element is shown in Figure 1a. These fibers can be of various shapes, sizes and made of various materials. For example, fibers can be couple of millimeters to a couple of centimeters long, straight, spiral or with different types of hooks at the ends, they can be made of steel, polymer, organic fibers, even glass [3]. In fact, one of the most commonly used types are hooked steel or glass fibers [4-7].

Adding fibers to concrete can greatly improve its mechanical characteristics in hardened state. For instance, if fibers are evenly enough distributed in the concrete matrix, the concrete compression strength, tension strength, toughness and ductility will be higher compared to the ordinary, conventional concrete, which has been reported in many researches, e.g. [8-10]. While the increase in concrete strengths can be as high as 80% [8], these fiber reinforced concretes are expansive and they are made only for special uses. For concretes used in practice the increase in strengths varies between 10-20%. However, the main contribution of the added fibers reflects in the dramatic increase of concrete's ductility. In the presence of fibers, depending on their quantity, concrete can be transformed from a very brittle material, to a distinctively ductile material. The described effect becomes most apparent when analyzing a force-displacement diagram or a stress-strain diagram of a structure or element, an example of which is presented in Figure 1b [11]. It can be seen that the post-peak behavior of the plain concrete and the fiber reinforced concrete is quite different – the plain concrete curve is much steeper, implying a more rapid material degradation, while the FRC expresses a very ductile behavior.

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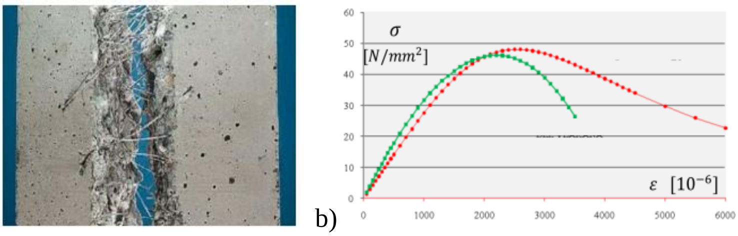
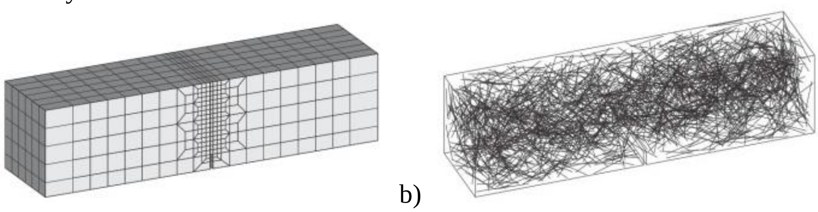


Fig. 1 a) A typical cross section of a fiber reinforced concrete element, b) A stress-strain diagram of a fiber reinforced element [11]

However, mathematical modelling of SFRC is a formidable task. While this challenge can be tackled analytically [12-14], this is applicable only to some simpler problems, while for more detailed solutions and results a numerical model is needed. Nevertheless, although there are several well-developed numerical models for the plain concrete, it is very hard to produce a numerical model that would describe the *fiber reinforced concrete* adequately, due to its highly complex behavior. To this date there is no one generally accepted way for the numerical modeling of fiber reinforced concrete, but there are rather several distinct modeling approaches.

1.2. Numerical modeling of fiber reinforced concrete

The oldest and the most commonly used approach for the numerical modeling of FRC is the modeling of FRC as a homogeneous material [15-21], very similar to conventional concrete modeling, with the appropriate values chosen for influential parameters so that results of numerical analysis would correspond to the results obtained by experimental testing of specimens. Parameters that differ from a conventional concrete model and that have the greatest influence on the behavior of FRC are the parameters related to the adopted concrete stress-strain diagram. The most important of these parameters are the compressive and tensile strength and the elastic modulus of concrete. A more detailed description of influential parameters and their values chosen for modeling FRC in this paper will be given later, while here only the main ideas and key features of different modeling approaches are presented. The mentioned type of modeling FRC is the simplest and also the most numerically effective one (it requires relatively modest computational resources), but on the other hand, it represents a much simplified model of the real material, which is distinctively inhomogeneous. While this model gives satisfactory results when modeling conventional concrete (e.g. [22,23]), for FRC it is much more sensitive to parameter variation and the obtained results depend largely on the right choice of the input parameter values, making it hard to use this model for predicting the FRC behavior without prior experimental tests, thus limiting its application in everyday practice.The next evolution step of numerical FRC modeling is an attempt to combine the advantages of a homogeneous concrete model with high computational power and modern numerical methods available nowadays. Namely, the idea is to model only the concrete matrix as a homogeneous material of appropriate mechanical characteristics, much like in a conventional concrete model, and to model the added fibers discretely, as a system of 1D finite elements (FE) randomly dispersed throughout the concrete matrix, as has been done in [24-27] for instance. An example of this type of modeling is presented in Figure 2 [26]. In this way the use of already well established parameters for concrete is ensured, while avoiding the need for experimental testing required to determine some parameters necessary for formulation of the fully homogeneous FRC model. For this modeling approach, the use of the Extended Finite Element Method (XFEM) is required in order to model the randomly dispersed fibers as *strong discontinuities* in the concrete matrix, while keeping the concrete and fiber FE meshes independent. Although this solution is more precise than the previously described one, it is far more numerically expensive, which again limits its application in everyday engineering practice. Beside this, it is important to define the appropriate fiber-matrix interaction in order to obtain reliable results, and the required data about the fiber-cement interface and interaction are not always available and they should be determined experimentally.



a) b)

Fig. 2 XFEM modeling of FRC; a) concrete matrix FE mesh, b) randomly dispersed fibers (1D finite elements) [26]

In the last decade more advanced numerical methods are being developed, which include modeling the material on several length scales – thus they are called multiscale methods. To the best of authors' knowledge, these methods have not yet been applied for the FRC modeling, but they are nevertheless mentioned here since the principles they are based on imply that they could successfully be used for this purpose. Namely, there are several types of multiscale methods, but only the most commonly used one will be presented here. In this method the tested specimen is usually considered as a *macro scale model*, and at this level the material is treated as homogeneous. However, its mechanical characteristics are not determined experimentally, but again on a numerical model that represents one small representative part of the macro model – a representative volume element (RVE). This scale is called *meso scale* and on this level all the distinct phases of the material – for example, aggregate, cement paste, voids, etc. - are modeled explicitly and in detail, also taking into account their mutual interactions and connections. Based on the results at the meso scale, the characteristics of the macro scale model are induced and through some homogenization process the required parameters are determined. The described numerical procedure is often referred to as the FE^2 method (Finite Element ^{2}) and it has already been successfully used in solving various problems [28-31]. The principle of deriving the characteristics of a model at one scale based on the analysis of the model at smaller scale can be repeated several times. Thus for instance, the characteristics of a meso scale model can be determined on a micro scale model, and its characteristics could in return be derived from a molecular model (through the use of Molecular Dynamics). In Figure 3a) approximate length boundaries for different scales are given [28], and for the purpose of illustration, in Figure 3b) a schematic representation of the multiscale method application for a concrete beam analysis is shown [29].

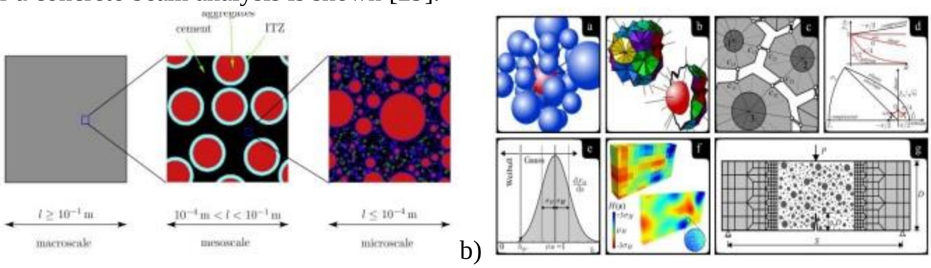
a) b)


Fig. 3 Multiscale methods, concrete modeling example; a) approximate length scale boundaries [28], b) multiscale modeling of concrete beam [29]

However, although the described methods enable very detailed modeling of material and prediction of its behavior, they are extremely computationally demanding and at this time they have only scientific and research value, but are not applicable in engineering practice.

Here it should be mentioned that there are some relatively recent, nonlocal methods such as peridynamics, where the equations of the Continuum Mechanics are reformulated to include also the nonlocal interaction of parts of the continuum [32,33]. These models are closest to reality since they can model the material behavior on all the length scales simultaneously, but such modeling requires enormous computational resources and is currently used only at some research institutes with massive CPU clusters.

1.3. Problem formulation and a brief paper overview

It can be concluded that the question of effective numerical modeling of FRC remains open and there is no one generally accepted model that would at the same time be sufficiently precise and computationally robust and simple for practical use.

Homogeneous material FRC model is fast, robust, simple and relatively accurate, but the results depend largely on input parameter values, that need to be determined experimentally. On the other hand, more complex, multiscale or non-local models are computationally much too expensive for everyday use.

The combined model with homogeneous matrix and discretely modeled fibers seems like a reasonable compromise between the accuracy and simplicity requirements. In this case, parameters are relatively standard and can be experimentally determined in common tests if necessary. However, in order to produce reliable results, these models require accurate fiber-matrix interaction description, introducing additional parameters and options not readily available in commercial softer packages, so various user-defined subroutines are required, e.g. [24-27]. Therefore, advanced programming skills are needed, which limits the use of these models in everyday engineering practice.

In this paper, a new approach for modeling FRC and numerical prediction of its properties is proposed. The aim is to reduce the amount of required experimental testing in the design of concrete structures, while also bridging the gap between the easy-to-use options readily available in commercial software and the use of a more detailed FRC model with discrete fiber modeling. The proposed approach was developed for Simulia ABAQUS software and it combines XFEM modeling capabilities already included in this software with some other available options for material modeling, in order to produce a fully applicable and sufficiently accurate FRC model without the need for writing complex user defined subroutines.

The proposed numerical modeling procedure was validated against experiment results. Since the main mechanical characteristics of hardened concrete are its compressive and bending tensile strength, these two characteristics were considered in this paper. First, an overview of the experimental testing performed by the authors, in the material testing laboratory of the Faculty of civil engineering and architecture in Niš, Serbia, is given. Next, the proposed numerical model is described in detail, followed by numerical results and their comparison to the experiment and some concluding remarks.

2. EXPERIMENTAL TESTING

2.1. Testing standards and used materials

All tests were done in accordance with the Serbian standards for testing the concrete in its hardened state [34] that were valid on the date of testing. All hardened concrete strengths were tested after 28 days of curing.

2.2. Compression strength

In accordance with [34], a compression strength was tested on cubes of 150x150x150mm dimensions in a standard hydraulic press up to the specimen failure.

2.3. Bending tensile strength

Bending tensile strength was tested on prisms 100x100x400mm, without a notch, in a standard 4-point-bending test. Prisms were simply supported on two steel cylinders symmetrically, with a clear span of 360mm, and loaded by a hydraulic press at thirds of the span, up to the specimen failure.

2.4. Fibers used

In all reinforced specimens, steel hooked fibers were used. The length of fibers was 50mm and their diameter was 1mm. Specific weight of the used steel was 7850 kN/m^3, and its specific tensile strength was 1200N/mm^2. Fiber steel elastic modulus was 210000N/mm^2 and its Poisson's ratio was 0.3.

2.5. Specimen labels, testing procedure and experimental results

In order to evaluate the proposed numerical model, the influence of different quantity of fibers on concrete strengths was tested. Namely, there were 4 series of 3 specimens for the two tested characteristics – 12 cubes and 12 prisms, producing 24 specimens in total. First series of specimens was not reinforced by fibers and it was used for comparison. Specimens of the other 3 series were fiber reinforced, with 0.5%, 1.0% and 1.5% of fiber-to-concrete volumetric share, respectively. Series labels, fiber quantity and experimental results for each series (average of 3 specimens' results) are summarized in Table 1. Specific specimen label consisted of the specimen geometry and series label followed by a specimen serial number, for instance "cube DS0-1", "prism DS5-3", etc. Figure 4 shows some of the tested specimens after the failure.

Fig. 4 Some of the specimens after the test

Table 1 Experimental testing – series labels, fiber quantity and experiment results

Specimen series labels	Fiber quantity (fiber to concr. matrix volumetric share)	Compressive strength (Averaged on 3 cubes) [N/mm^2]	Bending tensile strength (Averaged on 3 prisms) [N/mm^2]
DS0	0.0 %	43.11	6.67
DS4	0.5 %	45.45	7.18
DS5	1.0 %	53.98	10.22
DS6	1.5 %	51.91	10.32

3. THE PROPOSED NUMERICAL MODEL

All the conducted experimental tests were also modeled numerically, by using Simulia ABAQUS 6.14 software and following the procedure described in the following text.

3.1. Modeling geometry

Two types of numerical models were considered – cubes for compression strength, and prisms for bending tensile strength testing. Cubes dimensions were 150x150x150mm, while prism dimensions were 100x100x400mm. Both models are shown in Figure 5.

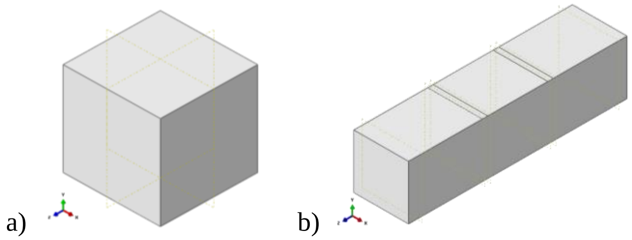


Fig. 5 Geometry of the used numerical models, a) cube for compression strength testing, b) prism for bending tensile strength testing

3.2. Boundary conditions

In the compression strength tests, it was assumed that there was no slip between the steel plate of the press and the contact face of the cube. Thus in numerical modeling, encastre boundary condition (BC) was set on the bottom cube face, and lateral deflections on the top side of the cube were prevented. The load was introduced by incrementally vertically lowering the top cube side for a certain deflection value.

In the bending tensile strength tests, prisms were simply supported, resting on two steel cylinders with a clear span of 360mm between the two contact lines. In numerical models, encastre BC was set along one of these two lines, while on the other the lateral displacements were prevented, and longitudinal were allowed. The load was also introduced through displacements, by vertically lowering the nodes in the region of contact between the prism and the other two cylinders conveying the hydraulic press load.

Boundary conditions for both models are shown in Figure 6.

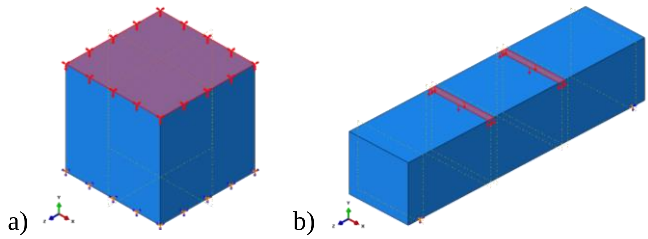


Fig. 6 Boundary conditions for the used numerical models, a) on cubes, b) on prisms

3.3. Finite element mesh for concrete matrix

As the XFEM was utilized, the plain concrete matrix could be meshed independently of the fiber distribution. Thus a regular mesh was adopted for both cube and prism models, using the ABAQUS standard 8-node brick finite element for mechanical analysis of solids. ABAQUS label for this FE type is C3D8R, and it was used with the following options chosen: linear, average strain and first-order accuracy. After the mesh convergence studies, the FE size of 10mm was adopted as both accurate enough and computationally effective. The used FE meshes for cube and prism are shown in Figure 7.

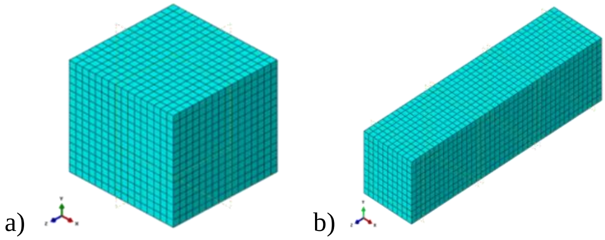


Fig. 7 Finite element meshes for concrete matrix, a) for cubes, b) for prisms

3.4. Material model for concrete

In experimental testing, the concrete mixtures were designed such as to achieve the concrete class of MB40 (The tests were done in accordance with the Serbian standards, the Eurocode equivalent for this concrete class would be approximately C35/45), following the recommendations in the Serbian standard for concrete and reinforced concrete structures design [35]. This fact was used to an advantage in numerical modeling. Namely, all the parameters for the (plain) concrete material model were calculated according to the mentioned standard, for concrete class of MB40. In this way an end-user of the numerical modeling procedure proposed herein only needs to define the targeted concrete class and all the parameters can be calculated without direct experimental testing, while using the wide and thorough tests already done and based on which the Standards were formulated. That been said, the main parameters for the concrete material model are presented in Table 2, along with their values calculated in accordance with [35] for concrete class of MB40.

Table 2 The main parameters for the concrete material model

Material parameter:	Measuring units	Value calculated for MB40 (according to [35])
Elasticity modulus (E_b)	[N/mm^2]	34 000.00
Cube ultimate compressive strength (f_{bk})	[N/mm^2]	43.11
Design compressive strength (f_b)	[N/mm^2]	25.50
Design tensile strength (f_{bz})	[N/mm^2]	3.07
Design bending tensile strength (f_{bzs})	[N/mm^2]	3.82

Stress-strain relation was also adopted in accordance to the mention Standard [35]. The adopted stress-strain diagram is presented in Figure 8.

In tension, tri-linear stress-strain relation was used, with stresses rising linearly with the increase of strain until the tensile strength is reached. Then follows the rapid decrease in stress until the half of the proposed ultimate strain, after which the stresses reduce to zero somewhat more slowly, as can be seen from the diagram.

In compression, the real, pronouncedly nonlinear concrete behavior was approximated by a parabola-straight line as shown on the diagram. The stress is related to strain by:

$$\sigma_b = 0.25 \cdot f_b (4 - \varepsilon_b) \varepsilon_b \tag{1}$$

for $\varepsilon_b \leq \varepsilon_B$, and $\sigma_b = f_b$ for $\varepsilon_B \leq \varepsilon_b \leq \varepsilon_{B2}$, where $\varepsilon_B = 0.2\%$ and $\varepsilon_{B2} = 0.35$. After that point, the stress reduces to zero bi-linearly, as shown.

In Table 3 all the preset stress-strain diagram points are listed for convenience.

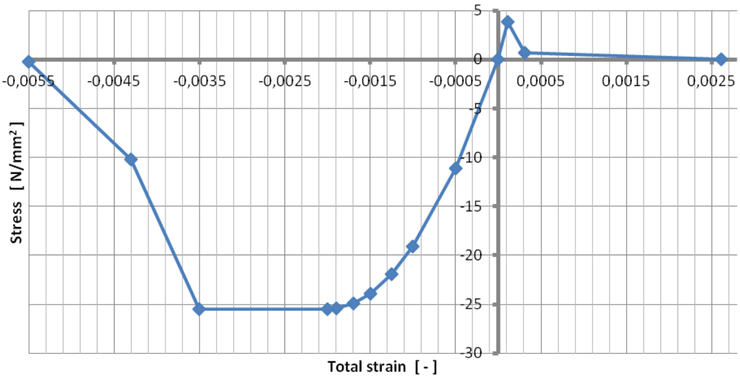


Fig. 8 The adopted stress-strain diagram for plain concrete

Table 3 The preset stress-strain diagram points

Points for the diagram in tension	Stress [N/mm^2]	Total Strain [-]	Plastic strain [-]
Point 1	0	0	-
Point 2	3.82	0.00011	0
Point 3	0.70	0.00031	0.00020
Point 4	0.01	0.00261	0.00250

Points for the diagram in compression	Stress [N/mm^2]	Total Strain [-]	Plastic strain [-]
Point 1	0	0	-
Point 2	11.60	0.00050	0
Point 3	19.13	0.00100	0.00050
Point 4	21.91	0.00125	0.00075
Point 5	23.91	0.00150	0.00100
Point 6	24.93	0.00170	0.00120
Point 7	25.44	0.00190	0.00140
Point 8	25.50	0.00200	0.00150
Point 9	25.50	0.00350	0.00300
Point 10	10.20	0.00430	0.00380
Point 11	0.26	0.00550	0.00500

In ABAQUS, the material model is formed as a combination of one or more elementary material models available in software, each having its own defining parameters. For the numerical modeling proposed in this paper, the concrete material model was obtained by combining two elementary material models – ideally elastic material (IEM) model and concrete damaged plasticity (CDP) model. There are only 2 parameters needed to define IEM model – elasticity modulus and the Poisson's ratio. In this paper, these values were adopted to be 34000N/mm^2 and 0.2, respectively. For CDP model, there are 3 sets of parameters required for material definition. The first group is comprised of the general concrete plasticity parameters and their labels and values adopted for this research are presented in Table 4. The second group of parameters is the set of stress-plastic strain tuples characterizing the points of the stress-strain diagram in compression, and the third one is set of these points for the part of the diagram in tension. Values used in this paper have already been shown in Table 3. No available suboptions for this material model were used.

Table 4 Parameters needed for general concrete plasticity model formulation

Parameter name	Measuring units	Value adopted for this research
Dilatation angle	[-]	31
Eccentricity	[-]	1
fb0/fc0	[-]	1.16
K	[-]	0.6667
Viscosity parameter	[-]	0.001

3.5. Modeling the fibers

The main feature of this paper is the procedure for modeling the fibers of FRC discretely, as a set of 1D FEs randomly distributed in the concrete matrix. As has been previously mentioned, in the current literature there are several papers on this modeling approach [24-27], but in each of them the fiber-matrix interaction is modeled explicitly, through some user defined subroutines. Namely, the XFEM enables that 1D FEs can be introduced regardless of the background concrete matrix mesh (nodes do not have to coincide). However, this method supposes that the embedded FEs are *ideally* bonded with the host region FEs, and it distributes the loads and material responses accordingly. In reality, fiber-matrix bond is achieved through adhesion at the contact interface, and this bond is not ideal. In practice, there are many cases of bond-slipping and fiber pullout, as well as fiber warping or breaking well before the ultimate fiber bearing capacity is reached. These effects largely influence the material response and they have to be accounted for in any numerical model with discrete fibers. This is usually done by including some user defined subroutines as already mentioned. However, these subroutines are often complex and require much knowledge in Continuum mechanics, FEM and ABAQUS syntax, so they cannot be expected to be widely used in everyday practice soon.

In this paper, an attempt was made to capture and model the main phenomena related to fiber-concrete interaction through the use of some options already available in ABAQUS software, avoiding the need for additional scripts. Namely, since the program uses XFEM, the ideal fiber-concrete bond is assumed and bond-slipping and fiber breaking are modeled by defining *separate material models* for each distinct fiber behavior. *Therefore, there were 3 fiber material models (FMM) defined*.

The first FMM (FMM1) simulated the perfect fiber-matrix bond, and the steel fibers were made of was assumed to have linearly elastic-plastic behavior. Thus the FMM1 was obtained by combining linearly elastic solid material model, with elasticity modulus of 210000N/mm^2 and Poisson's ratio of 0.3, and general plastic material model with isotropic hardening. In ABAQUS, the latter material model is also defined through a set of points in a stress-plastic strain diagram. These values were calculated for the yield strength of 1200N/mm^2 and tangent elastic modulus for plastic behavior equal to 1% of the elastic modulus in the elastic region, that is 2100N/mm^2. For plastic strains greater than 0.0163 the strain softening was introduced, so that stresses would decrease to zero at plastic strain of 0.0293. The resulting stress-total strain diagram is shown in Figure 8.

The second FMM (FMM2) was used to simulate the bond-slip and fiber pull-out behavior of the fiber-matrix interaction. The material model was defined in the same way as for the FMM1, only with a lower yield stress limit. After preliminary tests, it was adopted that a fiber would slip at approximately 66% of ideal fiber yielding strength, thus setting the yield strength for FMM2 at 800N/mm2. Also, the tangent elastic modulus was set to zero, and the ultimate plastic strain to 0.01, after which stress gradually decreases to zero at plastic strain of 0.02. The stress-total strain diagram is also presented in Figure 8.

The third FMM (FMM3) was used for fiber breaking simulation. It was the same as FMM1, only that there was no strain hardening after the material yield strength of 1200N/mm^2 was reached. To simulate the breaking behavior, a very steep stress-strain curve was adopted, as can also be seen in Figure 9. Stresses finally reduce to zero at plastic strains of 0.0063.

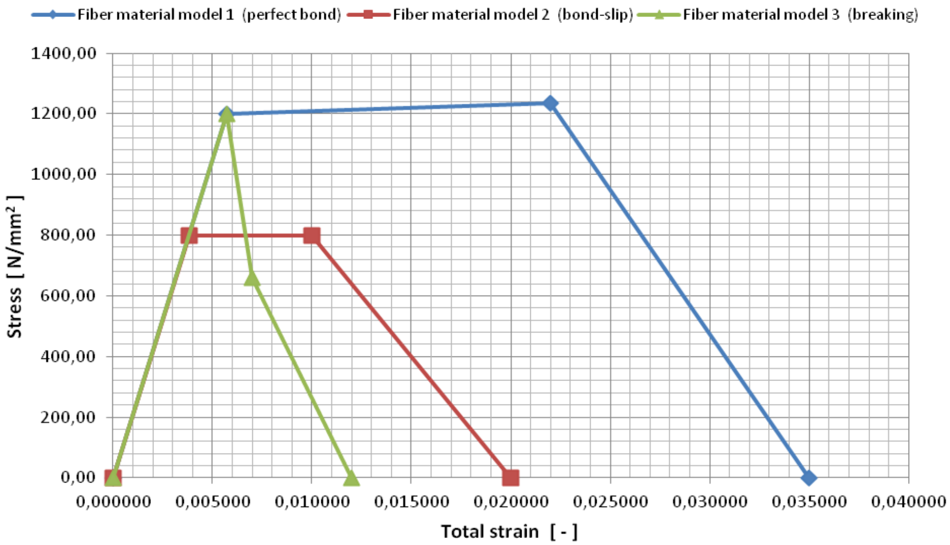


Fig. 9 Stress-strain diagram for the three fiber material models used

When all FMMs are defined, in an analysis each fiber would be randomly assigned one of the FMMs, thus simulating various fiber behaviors. In this way complex fiber-matrix interaction was modeled relatively simply, with no additional subroutines, only by using the XFEM option already available in the software. Due to a (numerically) perfect bond between the embedded and host FEs, hooks at fibers' ends would have minor or no influence on the solution. Therefore, fibers were model *without the hooks*, as straight cylinders of diameter of 1mm and length of 50mm, approximated with 1D FE of the corresponding characteristics. In ABAQUS, FEs of the type T3D2 were used, which are typical 3D 2-node truss elements for mechanical solid analysis. Number of fibers for each modeled specimen was calculated based on the volume of one fiber and the targeted fiber to matrix volumetric share (described in Section 2).

After the material models, geometry, FE type and total number of fibers were defined, they were randomly dispersed throughout the (already meshed) concrete matrix. The whole modelling procedure proposed in this paper is given as supplementary material in the form of a *python* script, readily executable in the Simulia ABAQUS software. Models obtained in this way for each of the tested FRC specimens are presented in Figure 10.

3.6. Solution procedure and analysis parameters

The load was introduced in 1 step with Maximum number of increments 1000, Initial ("time") increment size 0.01, Minimum increment size 1E-8, and Maximum increment size of 0.01. Direct Newton-Rhapson method was chosen as a solution technique with the geometric nonlinearity taken into account. Adiabatic heating effects were not taken into account, and a general nonlinear static analysis was performed.

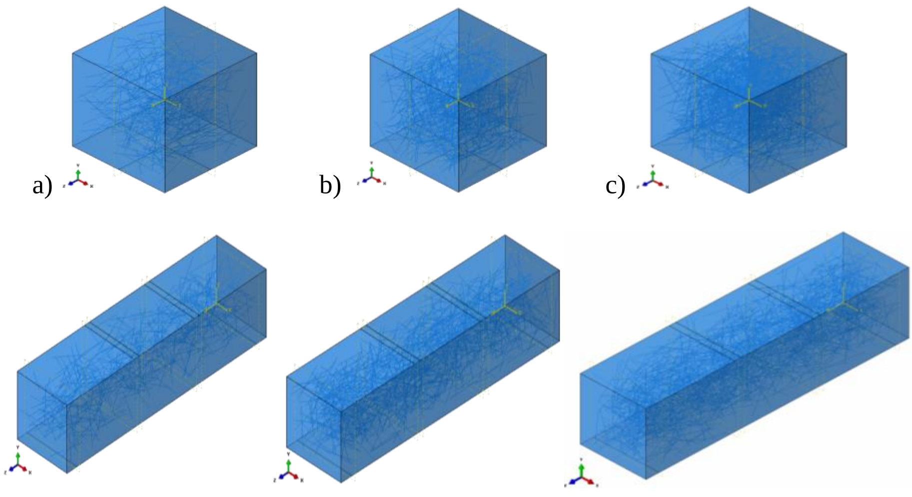


Fig. 10 FRC specimen models, a) 0.5% fibers, b) 1.0% fibers, c) 1.5% fibers

4. Results of the Numerical Analysis

The numerical results are displayed in the form of load-displacement diagrams for compressive strength tests and bending tensile strength tests in Figure 11 and Figure 12, respectively. All the results for the compressive strength tests are summarized in Table 5, where the experimentally tested and numerically obtained compressive and bending tensile strength for all the considered specimens are presented, along with the resulting difference. Similarly, all the results for bending tensile strength tests are summarized in Table 6. (All the results are averaged on at least 3 numerical analyses per specimen.)

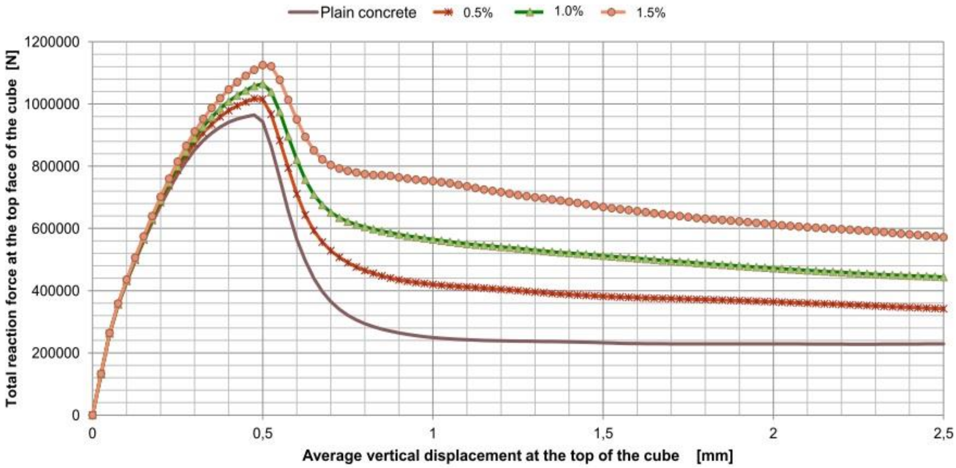


Fig. 11 Load-displacement diagram for compression tests

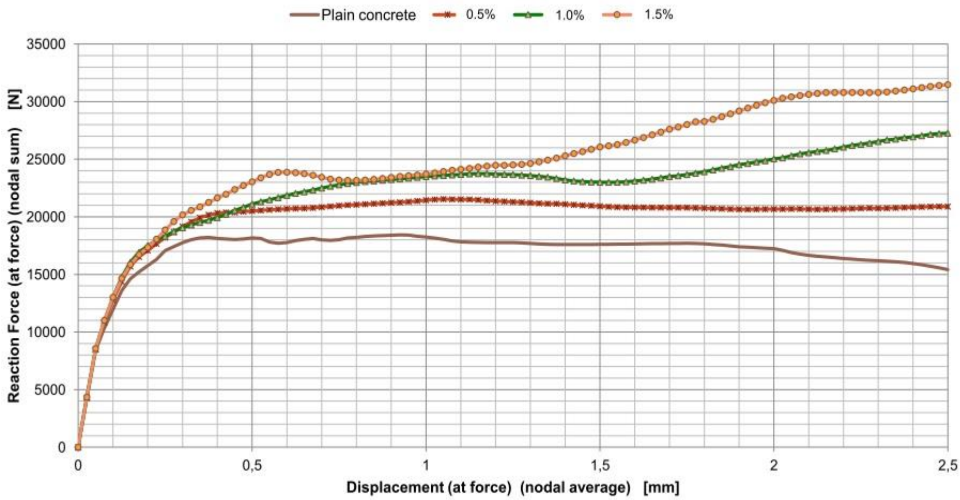


Fig. 12 Load-displacement diagram for bending tensile tests

Table 5 Results summary for compressive strength tests

Specimen series	Fiber to matrix volumetric share	Experimentally determined compressive strength [N/mm^2]	Numerically determined compressive strength [N/mm^2]	Difference
DS0	0.0 %	43.11	42.87	-0.56%
DS4	0.5 %	45.45	45.21	-0.52%
DS5	1.0 %	53.98	47.45	-12.10%
DS6	1.5 %	51.91	50.01	-3.67%

Table 6 Results summary for bending tensile strength tests

Specimen series	Fiber to matrix volumetric share	Experimentally determined bending tensile strength [N/mm^2]	Numerically determined bending tensile strength [N/mm^2]	Difference
DS0	0.0 %	6.67	6.64	-0.50%
DS4	0.5 %	7.18	7.75	+7.96%
DS5	1.0 %	10.22	9.81	-3.98%
DS6	1.5 %	10.32	11.33	+9.77%

4.1. Compressive strength tests comparison

Experimental and numerical results for compressive strength tests are shown in Figure 11 and Table 5. As can be seen from the diagram, the maximum bearing capacity of a specimen can be easily determined in terms of the maximum force the specimen can sustain. Maximum force divided by the area of one face of the cube gives the compressive strength. As it can be seen from Table 5, the results are in a very good agreement with the experiment for all the fiber quantities except for the specimen with 1.0% volumetric share of fibers (VSF). There are several possible explanations to this deviation. The first and the most probable one is that there was a mistake in the experiment, which is indicated by an odd trend – specimen with 1.0% VSF exhibits higher compressive strength (53.98N/mm^2) than the one with 1.5% VSF (51.91N/mm^2). Other possible explanations are also considered in the next Section.

4.2. Bending tensile strength tests comparison

Experimental and numerical results for bending tensile strength tests are shown in Figure 12 and Table 6. It can be concluded from the diagram that the presence of fibers greatly influences the model behavior and increases the specimen bending tensile strength significantly. However, numerical and experimental results differ somewhat more. As can be seen from Table 6, the results are in good agreement for specimens with plain concrete and with 1.0% VSF, while the deviation for specimens with 0.5% VSF and 1.5% VSF is larger. Although higher, deviations still remain within a 10% margin, which was considered acceptable for the numerical model in this stage of development. This deviation could be caused by several factors and these are also considered in the following Section.

4.3. General assessment of the proposed numerical FRC model

From the diagrams in Figure 11 and Figure 12, it can be seen that the general behavior of the proposed numerical model is reasonable and principally acceptable. Some general trends are noticeable:

- Adding more fibers induces higher material strengths.
- Adding more fibers significantly increases the specimen's ductility.
- Specimens' behavior in tension is nonlinear, although a linear stress-strain relation was adopted for plain concrete in tension, which implies a realistic simulation of the influence of the added fibers.
- In tension, for FRC models three distinct stages in material degradation can be observed (and they become more apparent with the increase of VSF) – a mostly linear elastic zone, a gradual material degradation zone, and a complete material degradation zone (horizontal part of the curve) – whereas the plain concrete specimens lack the second one.

Overall, it can be concluded that the proposed model does take into account the influence of fibers on the FRC behavior and it simulates this behavior in a generally acceptable way. However, in its current state of development this model is applicable for global FRC behavior evaluation, but needs improvements in order to describe complex behavior of FRC in detail and, hopefully, to enable numerical prediction of a real FRC behavior with an acceptable accuracy. Some of these improvements are discussed in the next Section.

5. Concluding Remarks

5.1. Result analysis and evaluation of the proposed model

In this paper a FRC model with discrete fiber modeling by using the Simulia ABAQUS software is presented. An alternative way to define the fiber-concrete matrix interaction is proposed and the obtained numerical results are validated against the results of the conducted experimental tests, for specimens with various volumetric shares of fibers. Numerical results are mostly in good agreement with the experiment, but there are relatively large deviations for some tested specimens. There are several possible reasons for this deviation:

Erroneous experiment – some unexpected trends are observed in both compression and bending tensile strength results. For instance, it appears as the specimen with 1.0% VSF has higher compression strength than the one with 1.5% VSF. Furthermore, the increase in bending tensile strength between the specimen with 1.0% VSF (10.22N/mm^2) and the one with 1.5% VSF (10.32N/mm^2) is very small (approx. 1%) compared to the increase between other specimens (average increase is approx. 30%), and the strength is much lower than expected. This could explain the considerable numerical error.

Random fiber distribution – since the fibers are modeled explicitly and are distributed *randomly* throughout the concrete matrix, this model is bound to produce somewhat different results with each performed analysis. Thus it is necessary to repeat the analysis many times in order to obtain a valid statistical average/mean result. Therefore, additional analyses were performed and a promising trend was observed. For example, the deviation in bending tensile strength for the specimen with 0.5% VSF was initially 12.56%, but after taking the average of 8 analyses it reduced to the presented value of 7.98%. This implies that the model could converge to a more accurate solution with an increased number of analyses. However, one of the main disadvantages of this modeling approach exhibits itself here – since the fibers are modeled discretely, the analysis is much more computationally expansive, and due to relatively limited computational resources, repeating the analysis sufficient number of times to produce a statistically significant population would require a very large amount of time. For illustration purposes, in Table 7 the evaluation time for models with different VSF is summarized. The analyses were done on a PC with Intel i5-7400 CPU 4x3.0GHz and 8.0 GB RAM. As it can be seen, the total evaluation time increases exponentially with the increase of volumetric share of fibers. Nevertheless, although with the current result the deviation in the results remains considerable, it is possible that it would diminish with larger number of repeated analyses, and this could be easily achieved with higher computational power.

Table 7 Average evaluation time in seconds for a single model of various type and VSF

Specimen	DS0 (0%)	DS4 (0.5%)	DS5 (1.0%)	DS6 (1.5%)
cube	182	2552	6192	10088
prism	562	2266	6480	10804

Insufficiently accurate fiber bond-slip behavior modeling – in this paper, fiber-matrix interaction was modeled through the use of different fiber material models (FMMs), and three distinct behaviors were considered – a perfect bond with yielding of fibers, a fiber-pullout with a bond-slip defect, and a fiber breaking. However, the bond-slip and fiber-pullout can occur at different stress levels, depending on the realized fiber-concrete adhesion. Various factors such as fiber geometry, concrete material structure in fiber area and cement hydration in vicinity of fiber influence this adhesion, making it very hard to predict the exact bond-slip stress (BSS) level. In this paper, after some preliminary analyses, BSS was adopted to be equal to two thirds of the fiber steel yield strength. Generalization of this type could have caused the mentioned numerical solution deviations. However, this is not very likely, since the results are in good agreement with the experimental ones for the rest of the considered specimen types.

Some other phenomena unaccounted for in this model – the proposed model considers some of the specific fiber-matrix and concrete behavior phenomena. However, many idealizations were also made, for instance: concrete matrix is modeled as a homogeneous material, fibers are geometrically perfect and evenly distributed (though randomly oriented) inside the matrix, and so on. Moreover, some phenomena such as concrete-wall interlocking effect and some others, perhaps yet undiscovered effects were neglected. These phenomena could also have led to the considered results deviation.

5.2. Possible improvements of the proposed model

In its current state of development, the proposed model produces results in reasonable agreement with the experiment. However, it can be greatly improved by introducing accurate fiber geometry (hooked end fibers) and a more precise fiber-matrix interaction, especially regarding the bond-slip behavior, and randomizing the bond-slip stress level within a certain range to simulate different possible conditions of fiber-matrix interface.

5.3. General conclusions and suggested directions for further research

The numerical FRC model proposed in this paper is robust, relatively accurate and simple to use, presenting a successful alternative to the commonly used models, and it can be improved to make it an even more accurate and comprehensive FRC model.

However, although promising, this model has certain drawbacks inherent to all the models of the discrete fiber modeling approach. It requires considerable computational resources to evaluate the model, and due to the random fiber distribution it requires many repeated analyses to derive statistically conclusive results. Moreover, it is not yet reliable enough to make accurate predictions that could provide a firm basis for structural design. This, combined with the high computational requirements, renders this model not yet applicable in engineering practice, thus partially neutralizing the advantage gained by simplifying a discrete fibers model and bringing it closer to a wider circle of end-users.

After all that was said, authors would still suggest that further research be mainly oriented towards improving and further developing the homogenous material FRC model, while models with discrete fibers such as the one proposed in this paper could be used to numerically estimate the parameters required for the homogeneous material model definition, thus reducing or even completely avoiding the need for experimental tests, which would make the design process cheaper and more efficient. In this way the advantages of both modeling approaches would be combined and they would complement each other, and the model proposed here could help in achieving this goal.

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PREDLOG NOVOG NUMERIČKOG MODELA ZA ODREĐIVANJE ČVRSTOĆE BETONA OJAČANOG VLAKNIMA

U ovom radu je prikazan alternativan numerički model za određivanje čvrstoće betona ojačanog vlaknima na pritisak i na zatezanje savijanjem. Vlakna su modelirana diskretno, koristeći Prošireni Metod Konačnih Elemenata (Extended Finite Element Method – XFEM). Predložen je i novi način modeliranja interakcije između vlakana i betonske matrice, bez potrebe za definisanjem dodatnih podrutina.Predloženi numerički model proveren je prema ekxperimentalnim ispitivanjima i rezultati se slažu u zadovoljavajućim granicama. Model je razvijen za rad u Simulia Abakus softveru (Simulia ABAQUS), ali je prikazana procedura opšte primenljiva. Na kraju su izložena i moguća unapređenja modela i predlozi njegove primene.

Ključne reči: *beton ojačan vlaknima, mikroarmirani beton, XFEM, model sa diskretnim vlaknima, interakcija vlakna i betona, numeričko određivanje čvrstoća*

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Original Scientific Paper

A PHASED CREATION OF DIGITAL ELEVATION MODEL FOR HYDRODYNAMIC MODELING IN FLAT ZONES

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Abstract. *Hydrodynamic modeling of rivers with flood simulation requires an accurate description of the riverbed and inundation morphology. Depending on a geodetic survey method and data collected, the digital elevation models with different accuracy can be created. This paper describes the methodology for creating a hybrid digital elevation model intended for hydraulic calculations, analysis, and results systematization and interpretation. The case study selected for illustration of the methodology is the flat ground area surrounding the Tamiš River in the Panonian Plain in Serbia. The production steps, advantages and disadvantages of the created digital elevation models with different surveying methods are explained, as well as the application of the hybrid digital elevation model for the 1D- and 2D- hydrodynamic modeling.*

Key words: *Digital Elevation Model (DEM), Flood Simulation, LIDAR, Hydrodynamic Modeling*

1. INTRODUCTION

Visualization of the terrain relief is commonly used nowadays for scientific, professional, and commercial applications. The Digital Elevation model (DEM) is a numerical and mathematical representation of the ground surface, most often in the form of a regular grid, in which a unique spatial elevation value is assigned to each pixel. DEM approximates the Earth's surface shape with a limited precision. The accuracy of terrain surface approximation depends on the distribution and density of the collected data by different types of geodetic survey [1].

In hydraulic engineering applications, flood-related hydrodynamic modeling requires precise geometry data on both floodplains and the riverbed morphology. The geometry of

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a surface, described in DEM, in hydrodynamic modeling can significantly affect the accuracy of the results, which can lead to erroneous conclusions in both research and engineering applications [2, 3, 4]. The same is reported by the group of experts from Europe [5]: the altitude data on DEM describing the potential floodplain of the river have a significant impact on the reliability and accuracy of the final results of conducted analysis. The vertical accuracy of DEM should be better than 0.5 m [5].

Previous studies have shown that DEM generated from geodetic surveys data can be used for various purposes [6], depending on its accuracy. The EU DEM [7] and other models with similar resolution do not provide high accuracy for hydrodynamic modeling in mountainous and hilly areas due to the large distance between two neighboring surveyed points and large terrain slope (10-30%) [8, 3]. Therefore they can be used for hydraulic calculations in lowland (flat) areas with a gradual or mild elevation changes. However, DEM accuracy has to be verified by field measurements [2], because in flat areas the aspect (direction of slope) is important and it can direct the flow to wrong directions.

Detailed and accurate digital maps and digital elevation models (DEM) are required to ensure the accuracy of inundation modeling as well as the identification of properties at hazard of flooding.

Nowadays, there is a variety of sources, tools and methods to generate DEMs. Ortho-maps are commonly used source to derive DEM from digital airborn and satellite images (horizontal resolution 0.5-2.0 m; vertical resolution 0.3-0.5 m). DEMs are also derived from the vectorised contour lines of 1:10,000 scaled digital map segments (terrain pixel size: 0.85-2.0 m; contour lines available in 1.0 m resolution). SAR (Synthetic Aperture Radar) acquisitions by InSAR (Interferometric Synthetic Aperture Radar) technique can generate high accuracy DEM and topographic maps. The radar can operate during the day and night and can penetrate clouds and rain. SAR technology is cost-effective and can generate DEMs with a vertical error of around 0.3 m, but also has the limitation and can not penetrate the water surface [9, 10, 11]. LiDAR (Laser imaging, Detection and Ranging) is the most accurate remote sensing method of 3D data acquisition for terrain and its coverage. The data obtained by terrain laser scanning from the air have the highest vertical accuracy up to 1 cm horizontal and 2 cm vertical, but have severe limitations under cloudy and rainy conditions and also can not penetrate the water. Laser beam reflects from the water surface and instead of riverbed under water, the elevation of the water surface is registered [9, 12, 2, 3]. For the precise hydraulic modeling, it is necessary to perform additional geodetic survey of the morphology under the water surface using classical geodetic survey methods or echo sounders, i.e. survey of the minor riverbed bathymetry. In this way, high precision of the complete riverbed morphology is obtained [2]. In addition, control geodetic surveys at characteristic points (e.g. base and crest of leveess, high roads, etc.) are desirable, in order to verify existing models and increase the accuracy of the boundary conditions for hydraulic calculations.

This paper presents the methodology for preparation of digital geodetic data sufficiently precise for the needs of hydrodynamic modeling in flat zones. The steps of development, advantages and disadvantages of the generated DEMs with different geodetic survey methods are explained.

The software packages ArcMap [7] and HEC-RAS [13] are used in the research, the latter due to its capabilities in the GIS (RAS-Mapper) module [12], where DEM can be processed and created, model geometry edited, and results displayed.

Based on the hydraulic analysis results and the final flood simulation, flooded areas are shown on the DEM, enabling flood hazard maps creation. A variety of flooding scenarios may be further studied in the prepared model including a dam break, and closing the gates, because the created DEM enables visualisation of simulated flow.

2. METHODOLOGY

2.1. Materials and Methods

The research is conducted in two phases. In the first phase, the hybrid DEM is created from multiple sources. The second phase is dedicated to modifications of the hybrid DEM according to the requirements of hydrodynamic modeling. The procedure applied in the research is roughly illustrated in Figure 1 and in more detail in Figure 2. The input data comprise a publicly available DEM over Europe (EU-DEM), DEM of major channel above the water surface obtained from LiDAR scanning data, and DEM of minor channel created from the boatborne echo sounder and conventional land survey methods.

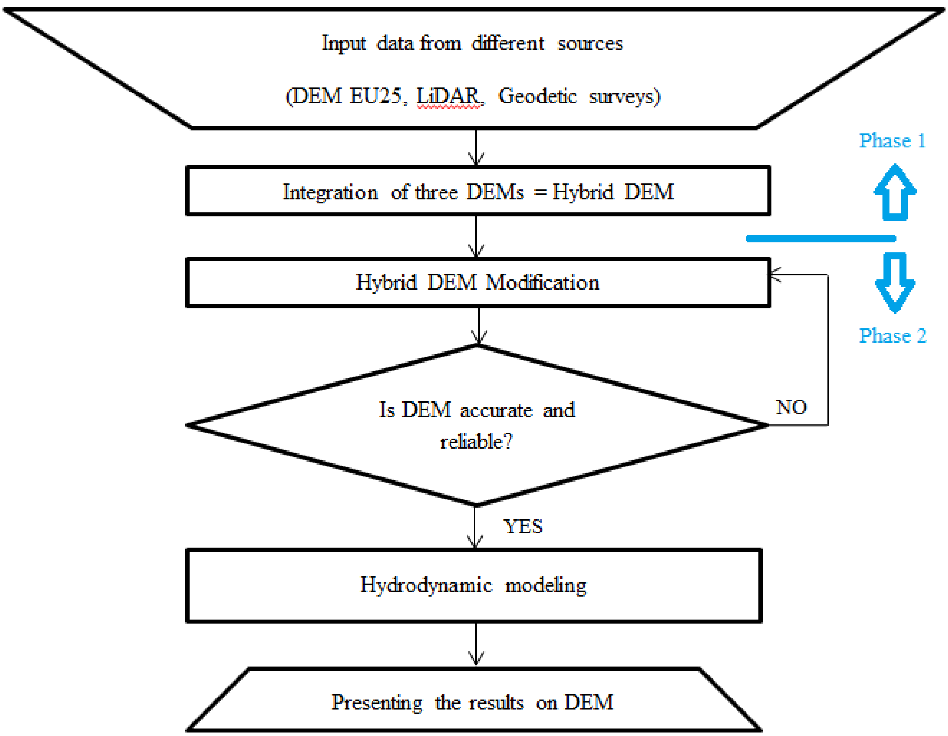

Fig. 1 Flow chart of hybrid DEM creation and use

The form of hybrid DEM requires a precision, accuracy, and reliability check in order to be applied to a case study of the study area. These criteria are quantified in section 3. The applied method and process of generation of the hybrid DEM form, which can be used to generate geometry on 1D and 2D models and hydraulic calculations, is shown in Figure 2.

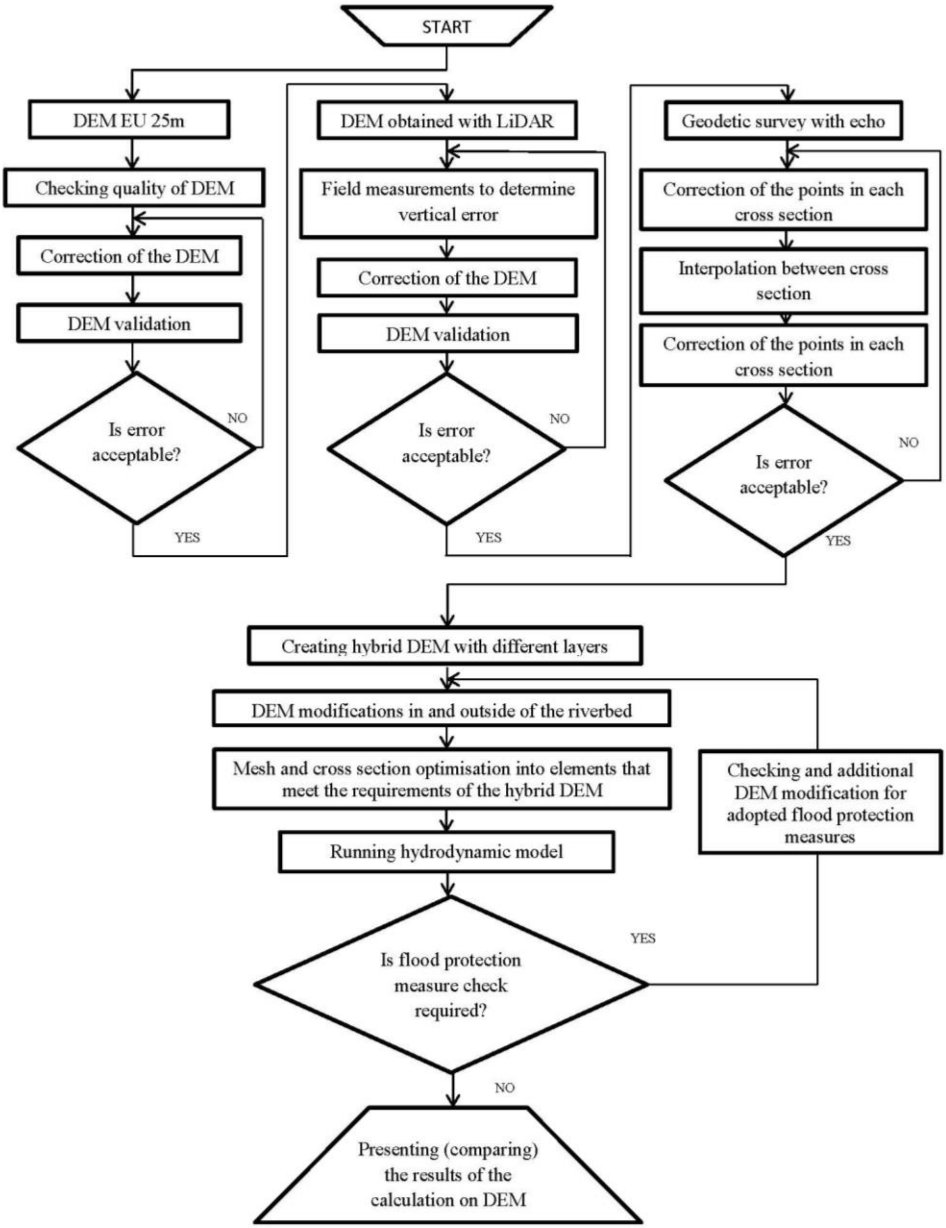

Fig 2. Methodology for hybrid DEM data preparation for interactive hydrodynamic modeling

2.2. Study area

The domain of the DEM and hydraulic analysis is the Tamiš River from the Danube River mouth (chainage: km 0+000.00), near the Town of Pančevo, upstream to the cross-section upstream of Baranda town (chainage: km 45+325.95), and the Karašac channel from the junction with the Tamiš River near Baranda to its inflow into the Danube River (Figure 3). On the analysed section the right-bank levee along the Tamiš River belongs to the Pančevački Rit flood defense system. On the left-bank, there are intermittent levees built from The City of Pančevo to Uzdin village.

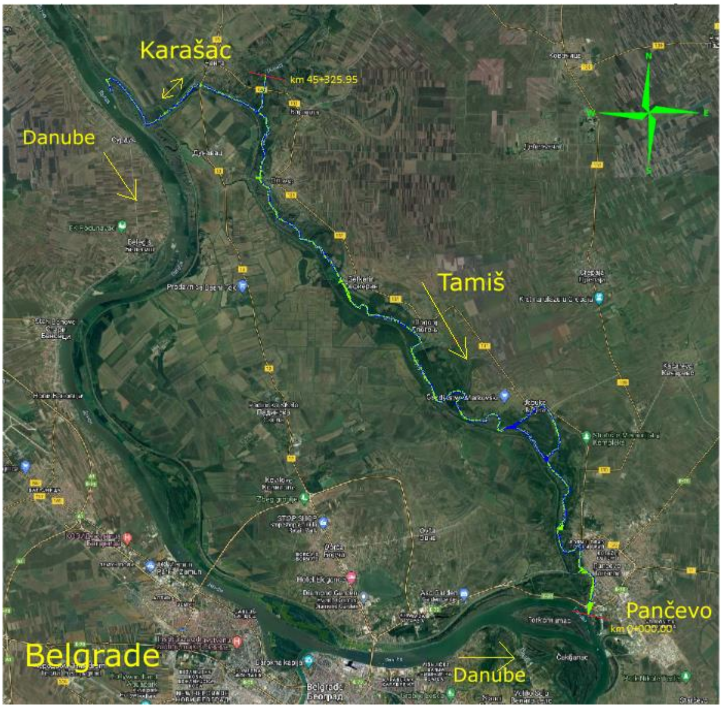

Fig. 3 Spatial domain of the hydraulic model and the DEM [3]

3. Creation of Hybrid DEM

3.1. Phase 1: Acquisition of source data

3.1.1. Digital elevation model EU 25 m

The first source for the development of the hybrid DEM for hydrodynamic modeling is a publicly available European DEM with a horizontal resolution of 25 m obtained from the 2013 Copernicus project managed by the European Commission. The statistical validation of EU-DEM v1.0 documents a relatively unbiased (0.56 m) overall vertical accuracy of 2.9 meters RMSE, which is fully within the contractual specification of 7 m RMSE. For the teritory of Serbia achieved RMSE is 3.18 m and mean error (ME) is -2.65 m. [8, 14].

Using the ArcMap software, the territory of the Republic of Serbia was cropped out and used for further generation of the hybrid DEM.

The EU DEM of 25 m resolution does not provide sufficient details [2]. The distance between two neighboring points of 25 m is too large for the intended purpose, and thin linear shapes and structures cannot be clearly recognized on the model. Levees, local roads, railway infrastructure, streams and similar features less than 25 m wide, do not appear on DEM (Figure 4).

Due to the low resolution of the EU DMT 25 m in most cases, especially in the flat zones, it is difficult to properly set the axis of the watercourse. Larger rivers with a width more than 25 m, such as the Danube River can be identified on this DEM, while the streams or smaller watercourses are often not even identifiable. In wide valleys or in domains with a slight change in terrain elevation, EU DEM 25 m is a useful source for the preparation of hybrid DEM for river basin studies.

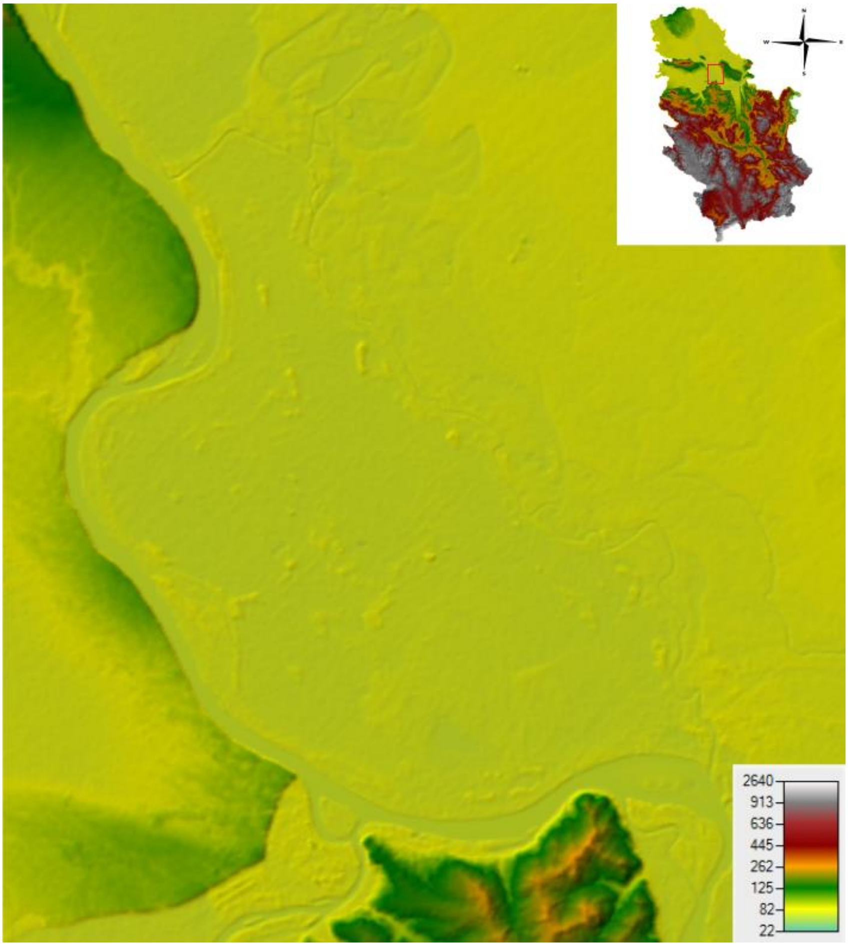

Fig. 4 The case study area DEM with a horizontal resolution of 25 m

3.1.2. Digital Elevation model obtained with LiDAR technology

A targeted laser scanning campaign of the subject Tamiš River area was conducted. The LiDAR technology belongs to the field of remote sensing, it measures the distance to an object or the surface of the Earth via laser pulses. Technology itself is based on measuring the time of sending and returning the reflected signal. Consequently, the three-dimensional (x, y, z) coordinates of each point are obtained. As a result of this kind of survey, a large number of points are obtained, representing digital surface model (DSM). The DSM is then filtered – the features not relevant for hydraulic modeling in flat areas are removed, and a high accuracy DEM of the analyzed area is generated in raster format with vertical accuracy of 2 cm, confirmed by conventional land survey. That confirms that the DEM obtained from laser scanning is the source of high accuracy for the implementation of precise hydraulic calculations, flood simulation, and for visualisation of the obtained results.

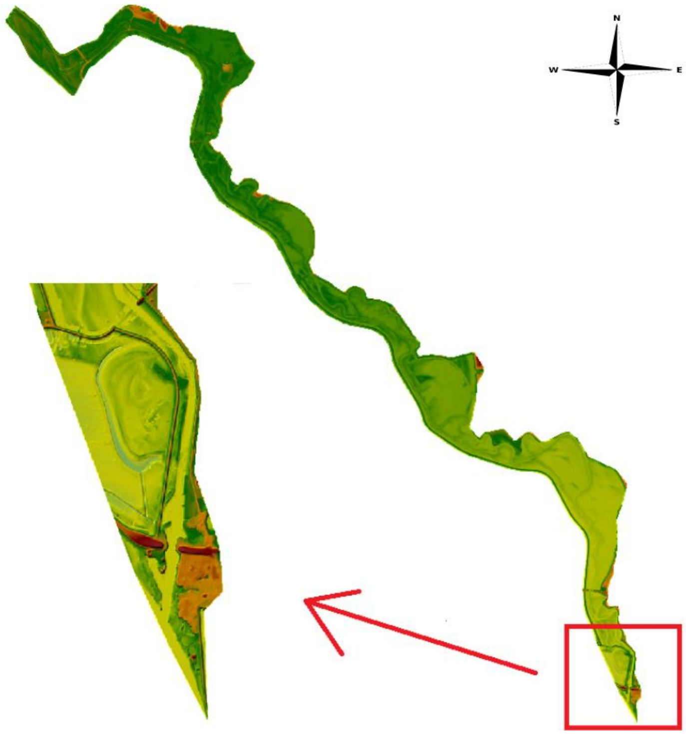

Fig. 5 DEM obtained with LiDAR technology

Although the LiDAR technology provides high accuracy, there are known limitations to its application related to the surface type and moisture content – it cannot penetrate water surface or water saturated media.

The shape of the watercourse is clearly visible on the analyzed section (Figure 5), and the model shows the water surface elevation at the time of survey (Figure 5 and Figure 6 – red line) instead of the riverbed configuration.

3.1.3. Digital Elevation model obtained from Geodetic survey

A field geodetic survey is performed for obtaining bathymetry data. A DEM that represents topography of seafloor or riverbed is also called Digital bathymetry model (DBM) [15].

Geodetic surveys of cross-sections were made from the natural Tamiš River estuary to the Danube River near the Pančevo Town, to the absolute stationing at km 45+325.95 and the entire watercourse of the Karašac from the junction with the Tamiš River to the junction with the Danube River (Figure 3). Parts of the cross-section were surveyed under water with echo sounder from the boat (Figure 6).

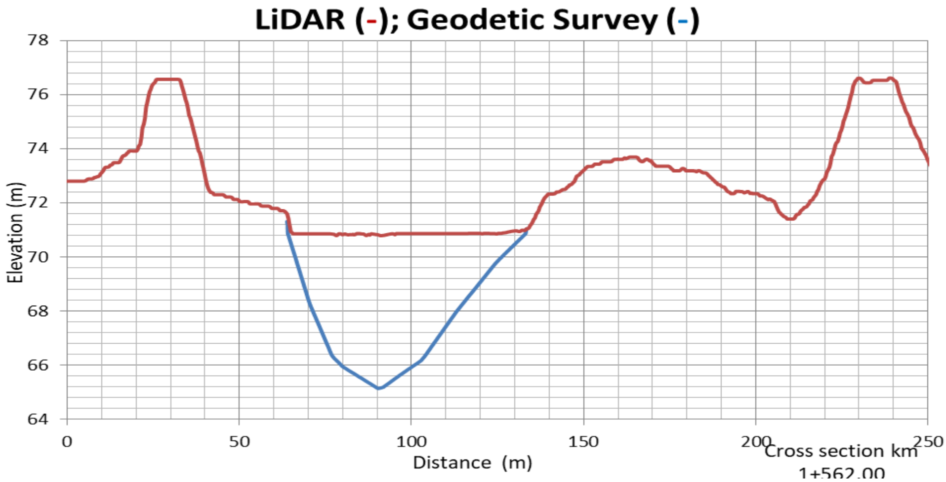

Fig. 6 Cross-section surveyed with LiDAR technology and the boatborne echo sounder

The detailed conventional geodetic survey of the features representing internal boundary conditions for hydrodynamic modeling (bridges, gates, junction) is also conducted on both watercourses.

Because the scanning with LiDAR technology and echo sounder were not performed at the same time, the water surface level from these two sources differed. When scanning with an echo sounder during the water elevation lower compared to the one during LIDAR scanning, certain parts of the riverbed were not surveyed at all. This problem was overcome by linear interpolation between two neighbouring vertical points in a cross-section [16].

The number and location of surveyed cross-sections is time&cost optimized and it was not adequate for hydrodynamic modeling. Therefore, a longitudinal interpolation of the riverbed is performed in HEC-RAS with approximate distance of 100 m along the river axis between the interpolated cross-sections. In order for the interpolation to represent the real riverbed shape as accurately as possible, the bank points for interpolation were set for adjacent cross sections [12]. Figure 7 shows the position of the cross sections along the studied river reach used to create the raster bathymetry DEM.

Fig. 7 Cross-sections in a part of the river reach used for creation of raster bathymetry DEM (RAS Mapper)

After the set of representative cross-sections was created in this way, a river bathymetry DEM (DBM) was generated in raster format with adjusted resolution of 10 cm, corresponding to the accuracy of the surveyed points with an echo sounder.

The RAS-Mapper automaticaly creates a DEM by taking altitude data from cross-sections using averaged elevation areas between them [12].

3.1.4. Creating hybrid DEM with prioritization of layers

The reference state coordinate system WGS 84/UTM zone 34N is used for all the three DEMs.

The hybrid raster DEM is composed in RAS-Mapper as a new terrain layer where all three DEMs are listed as input terrain files, prioritized, and the target vertical resolution is set to 10 cm [12]. Here, the lowest layer of the hybrid DEM is the 25 m resolution EU DEM, the next is the one obtained with LiDAR, and the final layer is river bathymetry DBM, the one constructed from a geodetic land survey. All DEMs are in the raster format. Stiching on the boundaries of different terrain layers is also performed within new terrain layer creation in RAS-Mapper, by triangulating surfaces between imported terrain models. The result is a continuous surface without peaks and sinks.

The quality of DEM was measured by comparing coordinates (x, y, z) of known points and corresponding points in DEM. Because of the terrain configuration in the study area, and built flood protection structures, the flow-accumulation image was not created and converted to main flow lines. The measures of the DEM quality are different in such cases and include number of broken flowlines, and average flow path displacement [17]. When fitting geodetic surveys of cross-section of the riverbed and levee points to LiDAR surveys, a hight consistency of 1-2 cm is found.

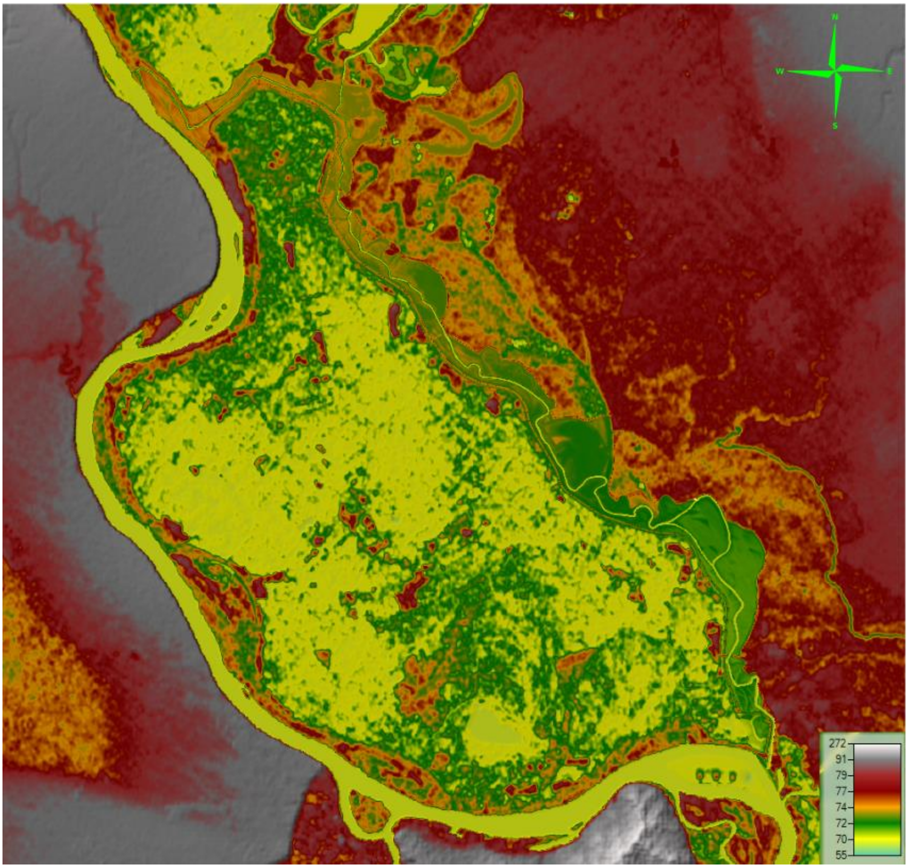

Fig. 8 Hybrid multilayer DEM of the study area

3.2. Phase 2: Finalizing the hybrid DEM

In the final DEM creation phase, corrections and modifications are made to provide a complete study area presentation of the appropriate accuracy for hydrodynamic modeling in flat area: minimum requirements are 10 m x 10 m horizontal and minimum 0.5 m vertical resolution [5].

3.2.1. DEM corrections and modifications to improve appearance of significant features

RAS-Mapper in HEC-RAS enables the terrain modification. Parts of DEM which have not been well captured by the LiDAR were filled in using land surveyed data on high terrain elevations i.e. patched in the GIS module.

Based on the surveyed elevations of the infrastructure objects, a modification of hybrid DEM was performed on the clone terrain layer, as suggested in RAS Mapper

Users Manual and levees and main roads were included in it [18]. After the modification of the DEM on the part of the DEM that covers the EU DEM 25 m, the roads are clearly visible but discontinuous, while riverbed is continuous (Figure 9a). This is due to terrain modification by “high ground option” selected as terrain modification method in RAS Mapper [18]. Also, upon the geodetic survey data, piers and a lock (Figure 9b) were inserted near the Pančevo gate.

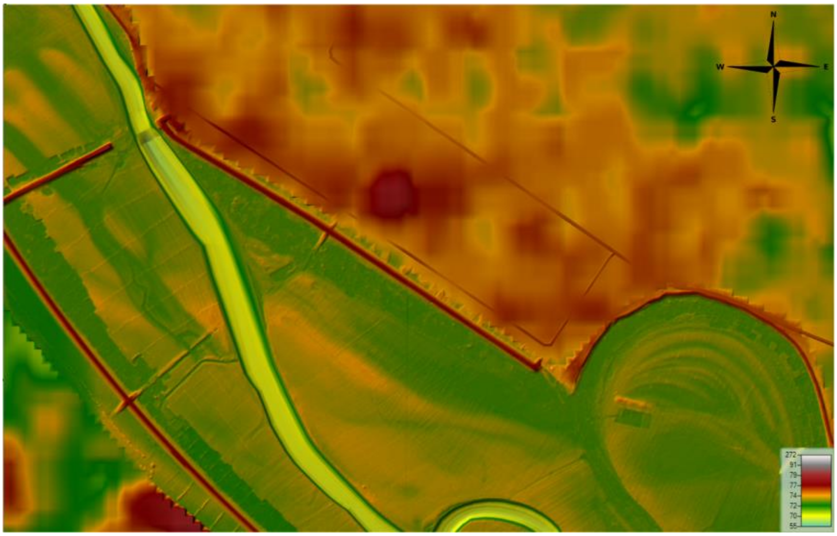

Fig. 9a Corrections of the DEM – the main roads added into the model

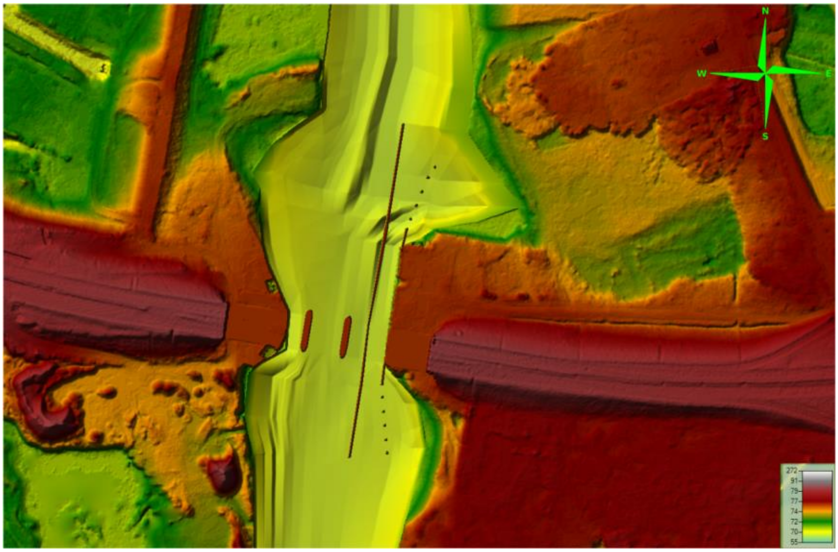

Fig. 9b Modifications on the DEM – lock and piers added

3.2.2. DEM use in 1D hydraulic model

The 1D hydraulic model requires geometric elements, i.e. computational cross sections, for establishing morphology functions and performing calculations between cross sections [19].

To have a stable numerical simulation, a larger number of cross sections than surveyed are required. Therefore, additional cross-sections are needed to provide the shorter distance (about 100 m) between them. The created hybrid DEM in its final form is used to generate cross-sections from the high elevation on the left bank to the right bank (Figure10). Due to the high resolution of DEM, there is a large number of points on the cross-sections. In flat inundations, such large number of points does not contribute to the accuracy of the calculation, but results in longer computational time. It is confirmed in this reasearch that reduction of the number of points in the cross-sections in flat inundation is recommended without any loss of the model accuracy [20].

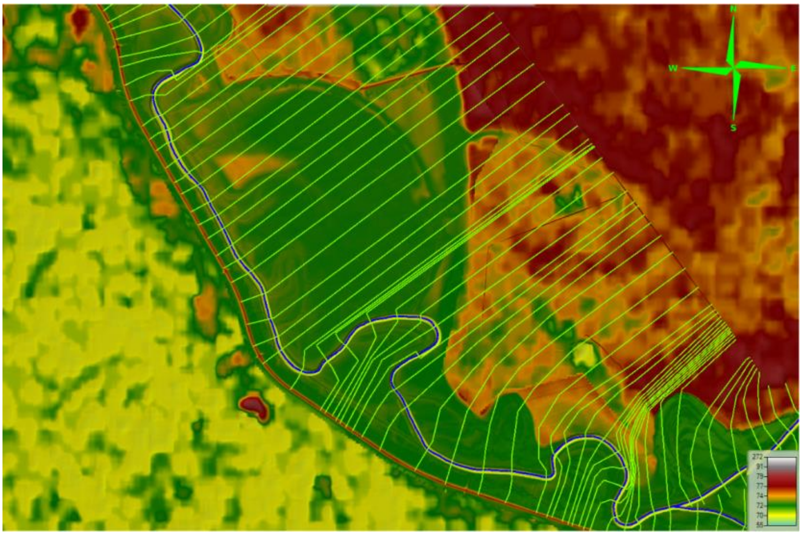

Fig. 10 1D model with generated cross-sections prepared for hydraulic calculations

3.2.3. DEM use in 2D- hydraulic model

The 2D hydraulic model uses computational mesh directly connected to the created hybrid DEM. The density of computational mesh cells reflects a change in elevation. Each cell size of the mesh can be considered a cross-section with its own detailed hydraulic characteristics.

In innudation, a high degree of calculation accuracy is achieved with 25 m x 25 m cell size. Smaller cell size and denser computational mesh contribute to a more precise calculation of fluid flow from one computational cell to another, which is required to provide at the locations of abrupt changes in the geometry of the riverbed and terrain. Here, in such places (levees, barriers, high terrain, roads), as well as in the main riverbed of the watercourses, the computational mesh is condensed and the size of cells from 2 m x 2 m up to 10 m x10 m is set (Figure 11).

If the cell size is not well set, it could happen that the levees are skipped in the calculation. The consequence is unrealistic flood in the protected and unprotected zone, as can be seen in the Figure 12. Figure 13 shows the difference between inapropriate and apropriate mesh generation at the location shown in Figure 12.

The total number of cells in the Tamiš computational mesh is 764,277 while the maximum cell area is 1,586.59 m^2, and the minimum is 1.61 m^2.

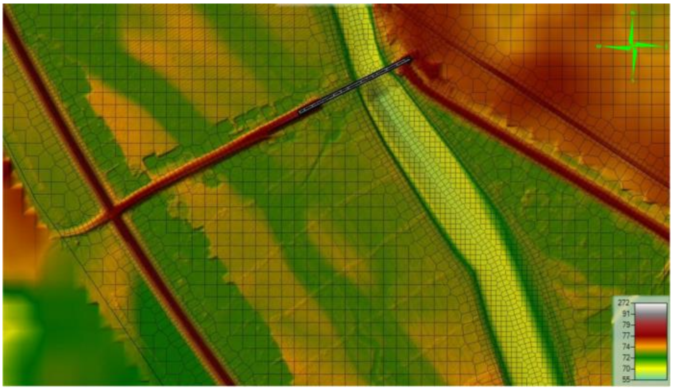

Fig. 11 2D model computational mesh - shape and size of cells

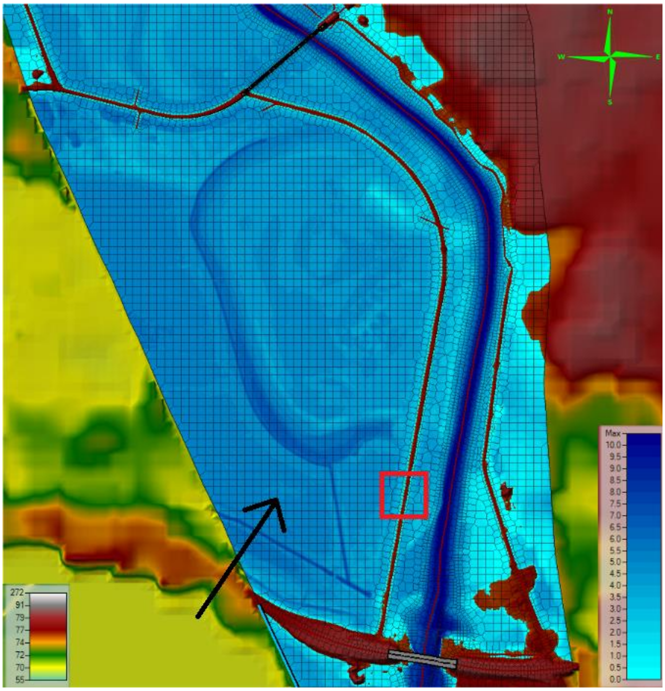

Fig. 12 Unrealistic flooding (as shown by black arrow) due to an inappropriate cell size in the computational mesh

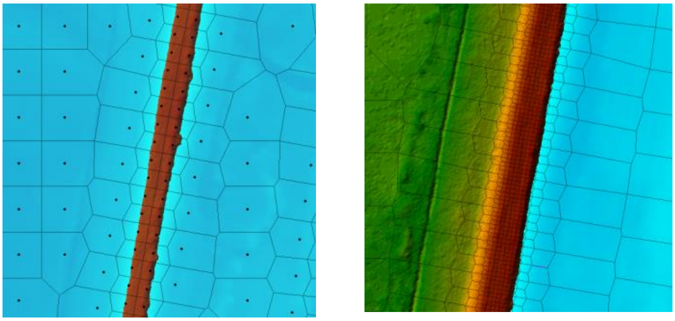

Fig. 13 Computational mesh of red rectangle in Figure 12**:** Left – inappropriate generation, Right – appropriate generation

4. The Hybrid Digital Elevation Model and Optimized Hydrodynamic Model Use for Flood Simulation

Upon the creation of hybrid DEM and optimized model, use of the model for flood simulation and visual presentation of flood wave propagation (usually combined with satellite image), a valuable decision tool is obtained [3].

The flooded area obtained by the 2D hydraulic model simulation for 100-year flood in the study area is presented below (Figure 14). Hydraulic calculations have shown that there is no overflow of the right-bank levee of the Tamiš River when the 100-year flood occurs. On the left-bank, several settlements are endangered during the 100-year flood due to insufficiently high levees, or their absence. The locations where water overflows the levees are shown on the hybrid DEM in Figure 15 and Figure 16.

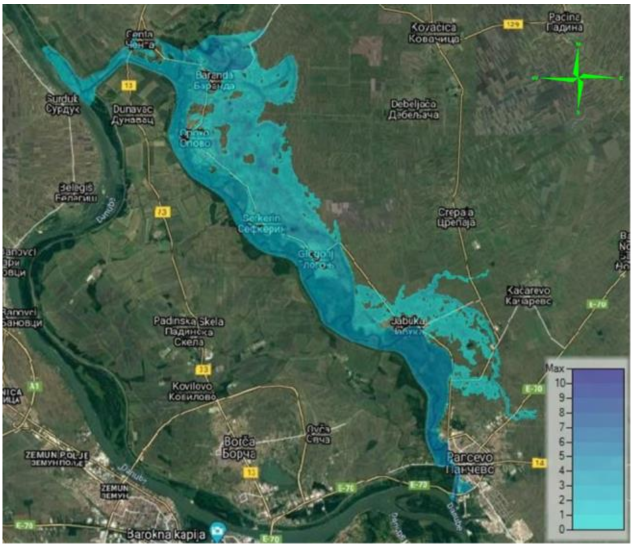

Fig. 14 Flooded area for 100-year flood in the existing condition

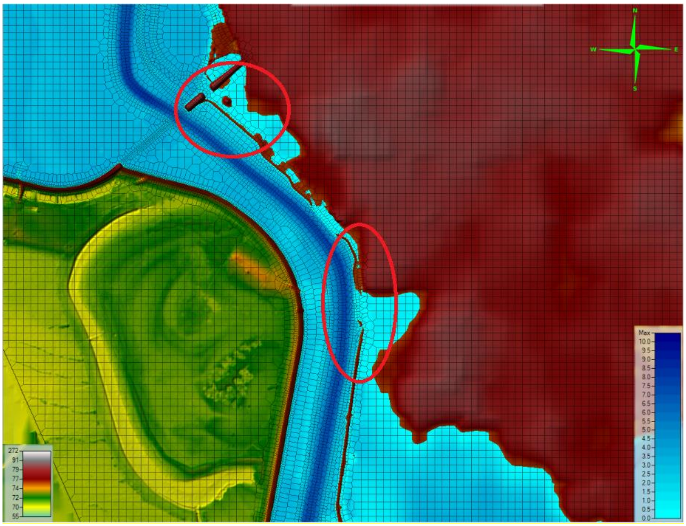

Fig. 15 The downstream section of the study area - Locations where water overflows the levees during 100-year flood shown on hybrid DEM

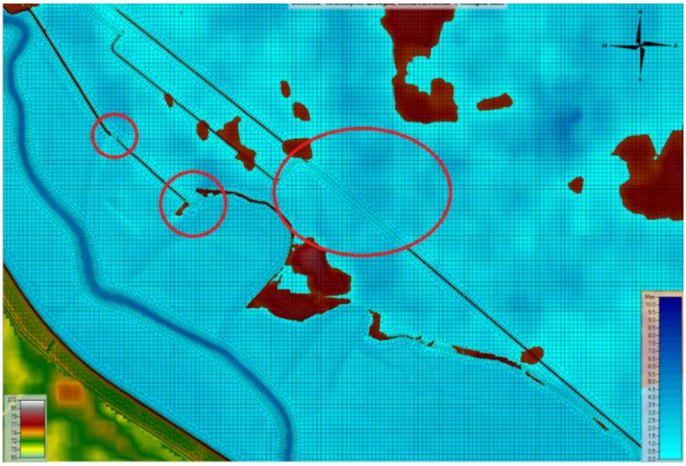

Fig. 16 The midcourse section of the study area - Locations where water overflows the levees during 100-year flood shown on hybrid DEM

Based on the 100-year flood simulation results in the present conditions, it is proposed to raise the right-bank levee by 1 m from the calculated water level. The rise of the existing levees on both banks was simulated by inserting additional modifications in the hybrid DEM. The results of hydraulic calculations on the altered hybrid DEM with raised levees scenario are shown in Figure 17 on the satellite imagery. In this scenario, the raised levees provide protection from the 100-year flood in the study area.

Fig. 17 100-year flood scenario with crest of the levees raised as a proposed flood protection measure

5. CONCLUSION

This reasearch systematizes steps in DEM creation for hydrodinamic modeling. The methodology was demonstrted in the case study area of the Danube River bypass consisting of the Karašac channel and the Tamiš River in Serbia. Considering the relevance of terrain configuration in hydrodynamic modeling, the accuracy of DEM is crucial for flood modeling. A hydraulic model based on low accuracy DEM would produce unrealistic results and may lead to wrong conclusions in both research and engineering applications. The methodology shown in the case study, consisting of a series of actions related to the preparation and processing of different elevation data, depicts one of the most difficult scenarios in digital elevation modeling.

A hybrid DEM was created in GIS environment (Arc Map, RAS Mapper) using EU DEM, LiDAR, geodetic land and bathymetry surveys as elevation sources. The 1D and 2D HEC-RAS hydrodynamic models are built by using a hybrid DEM as geometric input data source.

Based on the described methodology for phase development of DEM for hydraulic calculations, the following can be concluded:

1. The EU DEM at 25 m resolution is coarse to recognize thin linear shapes including levees, roads, railway infrastructure, and smaller watercourses;
2. The DEM obtained with LiDAR technology provides high accuracy. The research shows LiDAR levees elevation matches the elevation obtained by the field geodetic surveys at the accuracy of 1-2 cm. A large number of points on LiDAR based DEM on the other hand, sometimes overloads hydrodynamic simulations, and it is necessary to reduce the number of points in cross-sections. The main disadvantage of the LiDAR DEM is the inability to show the riverbed below the water surface,

and provide the inner geometry of the structures over the watercourse, relevant for flow simulation;

3. The geodetic surveys by echo sounder from the boat and land surveys of all structures crossing the riverbed, enables DEM finalization by providing the DBM or Bathymetry DEM (geometry of the riverbed under the water);
4. The hybrid DEM consists of prioritized DEM layers created from three data sources. With its modification for insertion of hydraulic structures and infrastructure (bridge piers, locks, levees, roads) it provides a precise elevation data source for generating a 1D and 2D hydrodyinamic model specific geometry;
5. The hybrid DEM can be further modified for simulating various flow conditions and flood protection measures.

Appart from measuring hybrid DEM quality by comparing coordinates of known points, other measures targeting hydrodynamic modeling should be considered. Future research steps should include flow accumulation image analysis by conversion to main flow lines and selection of adequate hybrid DEM quality measures.

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FAZNA IZRADA DIGITALNOG MODELA VISINA ZA HIDRAULIČKO MODELIRANJE U RAVNIČARSKIM PODRUČJIMA

Hidrauličko modeliranje rečnih tokova i simulacije poplavnih događaja zahtevaju dostupnost geometrijskih podataka koji dovoljno precizno opisuju morfologiju rečnog korita i inundacija. U zavisnosti od načina snimanja i prikupljanja podataka na terenu, kreiraju se digitalni modeli terena različite tačnosti. U radu je opisana metodologija izrade geodetskih podloga za potrebe hidrauličkih proračuna, analizu, sistematizaciju i interpretaciju dobijenih rezultata na primeru slivnog područja "Donji Tamiš". Objašnjene su faze izrade, prednosti i nedostaci dobijenih digitalnih modela visina različitim metodama snimanja, kao i primena kreiranih podloga za formiranje 1D i 2D hidrauličkog modela.

Ključne reči: *Digitalni model visina (DMV), LiDAR, Hidrauličko modeliranje, Simulacije poplavnog događaja*

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Original Scientific Paper

THE CONCEPT OF "SURFACE DEPTH" IN ARCHITECTURE

UDC 72.012.6

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Abstract. *In history of art and architecture, surface has always been the bearer of symbolic and aesthetic values, the subject of theoretical and critical analysis, with various ideological, discursive and philosophical interpretations. The subject of this research paper are different concepts of composition, artistic elements and materialisation of façade surfaces, which have the effect of "surface depth" as their primary characteristic. By analysing the potential of this concept in articulation of the structure of façade and other surfaces, three main emergent forms were noted: plasticity of surfaces (the use of small façade plastics), double skin façade with unused in-between space and double skin façade with used in-between space. By conducting scientific analyses of theoretical reference sources and characteristic examples, along with the application of the deductive methods, the characteristics of the „surface depth" concept in architecture were explored, with the aim of systematizing the principles used to achieve it, the possibilities of its application, as well as ways to establish the dual character of spatial planes - surface and volume. This research has contributed to the clarification of this concept and laid the foundation for further research in the direction of finding, chronologically ordering and analysing other examples, in order to enable their more extensive typology and systematization.*

Key words: *architecture, expression, concept, surface depth, double skin façade*

1. INTRODUCTION

A surface is a two-dimensional entity in Euclidean space that can appear in the form of a region, shape, or infinite plane. In theoretical terms, the surface has two sides that can be viewed from opposite directions. The term can also stand for the furthest or the highest layer of a physical object or space, which the observer can first perceive using the sense of sight or touch (Sparke, Fisher, 2016). In the fine arts, "depth of surface" is usually associated with the illusion of spatiality, which in painting is equated with the term "depth of painting" (Friedenwald, 1955). The ways in which the depth of space is achieved in a painting are

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diverse and usually imply the application of some form of perspective (linear, aerial or coloristic), proportioning objects (*Scale Shift*), etc. In architecture, the surface is one of the essential elements of architectural expression and appears as an indispensable part of every concept. In most cases when it is mentioned, the surface means the external or internal visible side of the façade, roof or some other architectural element. In certain situations, when another close *spatial plan*[1], can be seen through the surface, usually physically connected, such a surface is said to have a third dimension or depth (Fig. 1).

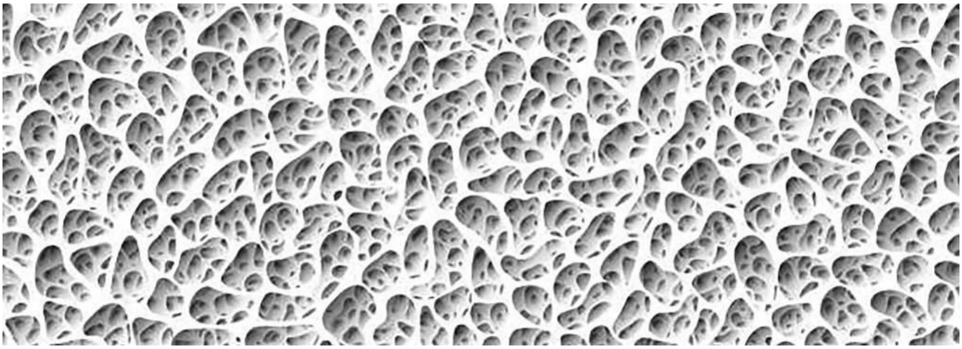

Fig. 1 Surface depth principle (Source: author's archive)

The subject of this research will be different concepts of composition, art and materialization of primarily façade surfaces, which exhibit the effect of "surface depth" as their primary characteristic. Using the deductive method, the characteristics of the concept of "surface depth" in architecture were investigated. By analyzing reference theoretical sources in which the meaning of the term is mentioned, as well as characteristic examples where this concept is present, the most important principles that determine the characteristics of the concept were extracted, with the aim of systematizing the principles by which it is achieved, the possibilities of its application, as well as the way of establishing a dual character of spatial planes - surface and volume.

The objectives of the research are: a) to consider characteristic examples and systematize the principles leading to achievement of the concept of "surface depth", b) to explore the possibilities of its application in architecture, and c) to re-examine the hypothesis that the concept of "surface depth" is achieved by placing parts of the basic surface into one or more secondary spatial planes according to the principle of depressed relief, whereby the resulting structure has a dual character - surface and volume.

[1] The term "spatial plan" in architecture can have several meanings. In this context, it stands for the distance of an element or surface in space from the position of the observer. The closer an element (surface or shape) is to the observer's eye, the closer plan position is considered to be. In this context, there are, the first, the second, the third, etc. plan, as well as the foreground or the background plan (Janson, Tigges, 2014).

2. Review of References

The concept of "surface depth" in this formulation has not been researched in science so far, although, all over the world, numerous examples of architectural objects can be found where this concept is present to a certain degree. However, some authors use this term to clarify their architectural concepts.

When talking about his building Zepter Palace in Belgrade (arch. Branislav Mitrović, arch. Vasilije Milunović, 1997), Branislav Mitrović states that: "the dynamics of the in-between space vacuum in the entrance area, the contrast of the wall (history) and glass-steel (technology) create the impression of "depth of surface" in the decomposing of envelope into layers. What appear to be the two faces of the house enabled a range of dialogues with: history, the spirit of the place, the architecture of the context, the neighbours, the time when the building was created ... " (Alfirević, 2013:76)

In a similar context, Frencis Ching uses another term "depressed base plane", which means a horizontal plane imprinted on the ground floor (or the ground) plane and uses the vertical surfaces of a lowered area to define the volume of space (Ching, 2007). Numerous authors build on Ching's interpretation and use the formulation of "depressed base plane" to describe the concept of plane distancing or depressing, thus achieving the effect of depth (Su, 2018; Seker Ilgin, 2008; Dahanayake, 2004; et al). Although Ching's term has, to a certain extent, already been accepted in architecture, this paper will use the term "surface depth concept", as pulling or pressing the surface is only one of the techniques used to achieve this concept.

This topic requires that we mention the position of the architect Kim Seunghoy, who in his essay *Depth of the surface - the potential of space* states that the task of creating the depth of the surface is not only to define the location's identity, but also concerns the "intermediary relationship" between the interior and the exterior. As the depth of the surface increases, it eventually turns into an in-between space. Using this space created on the boundary surface as a medium, the inside world communicates with the outside world" (Seunghoy, 2020). According to Seunghoy, the surface can have different depths. As the depth of the surface becomes larger, the surface is the first to become relief-like, i.e. it turns into multiple spatial layers, and then a third space (in-between space) is formed on the border between the exterior and the interior.

3. "Surface Depth" in Architecture

It has not yet been discovered when the concept of "surface depth" was deliberately applied for the first time in history, although indications of similar reasoning can be seen as far back as in the works of ancient Egyptians, who very early began to use the "sunken relief"[2] technique in surface treatment. The application of this technique involved engraving (cutting) the artistic representation in the stone surface and was used in various situations, from the decorative treatment of surfaces on the walls of tombs and temples, all the way to the façade at the entrances to tomb temples (hypogeum) (Fig. 2)

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[2] "*Indented relief*" is a relief sculpture technique where figures or images are carved in low relief, but placed inside a sunken area, so that the relief never rises above the basic flat surface.

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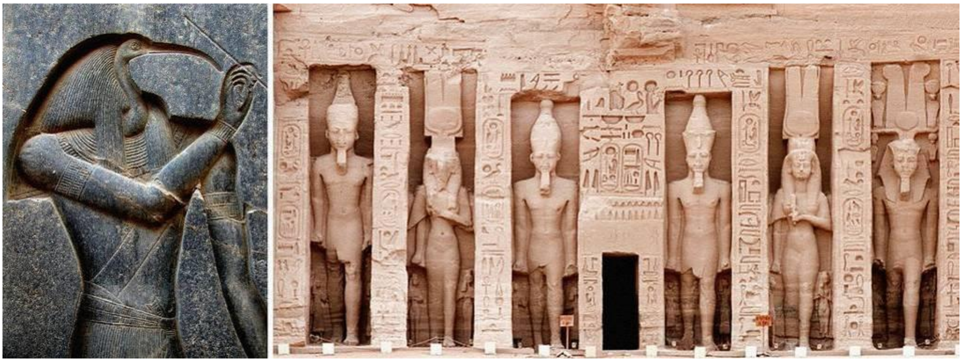

Fig. 2 Egyptian god Toth, Luxor temple, Egypt (left) (Source: Wikipedia, photo. Jon Bodsworth); Temple of Hathor and Nefertari, Abu Simbel (XIII c. BC) (right) (Source: Wikipedia)

Over time, the technique of sunken relief was relegated by other sculptural techniques showing the shape (shallow and deep relief) in a more spatial way. The significance of this technique is, among other things, that it has the effect of uniting pictorial and sculptural art as a whole. Throughout history, the use of relief in architecture has been widely used, primarily decoratively, in almost all cultures.

However, the emphasis in this research is not on the application of relief and its decorative role in architecture, although it is in some sense covered by "surface depth" concept, the focus is shifted on the potential of this concept in articulating the structure of façades and other surfaces, which is an area of a higher order, as it can affect both the spatial and functional organization of the house. If we consider theoretical possibilities of achieving the concept of "surface depth" in architecture, as in way was suggested by Kim Seunghoj, too, we can notice three main emergent forms:

a) plasticity of surfaces (application of small façade plastics),

b) double skin façades with unused in-between space, and

c) double skin façades with used in-between space.

3.1. Surface plasticity

The concept of surface plasticity is closely related to the term "extreme articulation", first promoted in science by Charles Jencks (Jencks, 1993, 1979). In a stricter sense, extreme articulation is a term that appeared in architecture in the 1960s and 1970s and refers to the reaction against empty and "boring" surfaces of modernist buildings. In a broader sense, the terms "surface plasticity" and "extreme articulation" can be equated because they refer to approaches that appeared on several occasions throughout history (Baroque, Gothic, brutalism, etc.), referring to radical or extreme approach to solving relief, i.e. surface expressiveness. The topic of surface plasticity can be viewed from two aspects, through application of: a) primary plastics (bay windows, loggias, avant-corps, etc.) and b) secondary plastics (decorative elements). Depending on whether there is a functional justification for the introduction and application of plastic elements, we can talk about whether and to what extent the expressionist character is present in the building concept (Alfirević, 2016, 2015).

The projects carried out by some architects at the beginning of the 20th century, such as Hans Poelzig, Wassili Luckhardt and Fritz Höeger, had certain characteristics of surface plasticity. Their aspiration was directed primarily towards the division of surfaces into a complex compositional system of spatial (depth) plans, consisting of profiles, fluting, pilasters, niches and the like. In the middle of the 20th century, as a part of the brutalist movement, numerous architects strived to achieve the plasticity of façade surfaces by applying deep reliefs treated in raw concrete, but their basic role was mostly decorative. There were rare examples such as the Elephant and Rhinoceros Pavilion in London (arch. Hugh Casson, 1965), where the rough relief treatment of façade surfaces was supposed to be associated with animal skin. Recent examples include Bruder Klaus Chapel in Mechernich (arch. Peter Zumthor, 2007), in which the depth of the interior surface was achieved with accentuated fluting (Fig. 3).

Fig. 3 Application of small façade plastic: The Elephant and Rhinoceros Pavilion, London (Hugh Casson, 1965) (left); Romtelecom Headquarters, Cluj-Napoca, Romania (Vasile Mitrea, 1969) (middle); Bruder Klaus Chapel, Mechernich (Peter Zumthor, 2007) (right) (Source: www.archdaily.com)

From what we mentioned so far, it can be concluded that the term "plasticity" of the surface implies primarily planning (articulation) of secondary elements on the façade: fluting, joints, pilasters, but also larger elements such as bay windows, balconies, loggias, etc. The effect of "depth" of the façade surface is achieved by indenting, pulling, slanting or twisting in relation to the basic, referential plane of the façade.

3.2. Multi-layer façades with unused in-between space

In many modern buildings, multi-layer façade systems have been applied, based on the principle of dividing the façade into two or more elements in depth. Such systems usually consist of an outer membrane, an in-between space and an inner façade. In most cases, the application of these systems is motivated by the inclination to preserve energy, but also by aesthetic (artistic) motives. The presence of external layers in front of non-transparent parts of the façade may have a slight impact on the building performance aspects, however, in cases when these layers cover the windows, one can notice a significantly weaker impact of daylight and decrease in energy performance in the interior (Paule *et al.*, 2017).

If the outer membrane of the façade, usually glazed, perforated or in the form of a brise-soleil, is placed in front of a window on the south, southwest or west façade, then it can play a functional role in shading the interior and preventing it from overheating (Boake *et al.*, 2002). Out of the different types of layered façades, the most commonly used are "double-skin façades"[3], made of two membranes placed in a way that allows the air to flow freely in the space between them (Arons, 2000; Hilmarsson, 2008)[4] (Fig. 4).

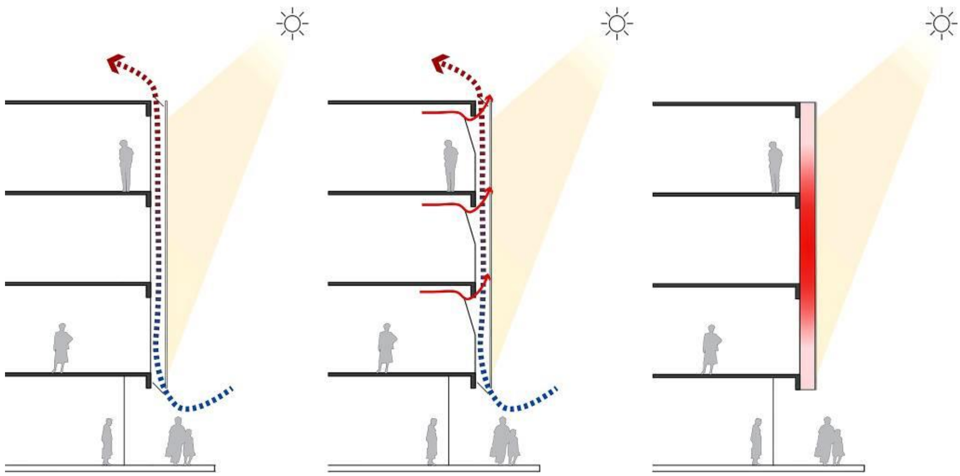

Fig. 4 Principles of functioning of a two-layer façade (Source: Souza, 2019)

Contrary to the generally accepted interpretation of a two-layer façade, where the essential feature is the uniformity of both layers, so that circulation can be achieved and the in-between layer can be ventilated, in some cases the outer layer is significantly perforated, which prevents steady air flow. Although the ventilated two-layer façade is a specific form of technological innovation, increasingly used in architecture in recent decades, there are a number of solutions that pay significant attention to the appearance and artistic aspects of the outer layer or the whole, at the cost of giving up the benefits brought by the two-layer system. This application of "layered" façades is formalistic, as the visual criterion is set above others (functional, technological, etc.), and the application of the concept of "surface depth" is primarily aesthetic (Fig. 5).

3.3. Multi-layered façades with used in-between space

A well-conceived functional organization of the building can result in the rooms being arranged in such a way that by pulling them towards the center of the building, the effect of "depth of surface" can be achieved on the façades. In residential buildings, it is common to position the living space in the zone along the façade, as this space, due to the frequency of use, requires a direct or indirect contact with the natural light and ventilation. In public buildings, by following a similar principle, rooms that are more frequently used and in which users stay longer are positioned along the façade. The space between the basic plane of the

[3] The principle of "two-layer facade" was first mentioned in 1849 by Jean-Baptiste Jobard, director of the Industrial Museum in Brussels (Saelens, 2002), while the first application of this principle is associated with the Steiff Factory (1903) in Germany by Richard Steiff (Poirazis, 2004).

[4] The distance between the layers usually varies from 20 cm to 2 m. The advantages of two-layer facades compared to single facades are most often improved sound insulation, protection of shading elements and providing natural ventilation in the interior. On the other hand, if the facade is poorly ventilated, i.e. if the in-between space of layers is inadequately designed, this can create problems of overheating of the interior space during the summer (Poirazis, 2008).

Fig. 5 Formalistic approach to the application of the concept of surface depth: Hexalace, Mohali (Studio Ardete, 2018) (left), Tessalace Commercial Office Space, Mohali (Studio Ardete, 2021) (right) (Source: www.archdaily.com)

façade and the withdrawn plane, the so-called in-between space, often has terraces, loggias, galleries, etc., areas which are transitional spaces, making up the interior, but also open to the outside. Depending on the degree of openness of the in-between space to the environment, the concept of surface depth may be more or less obvious. If indentations (recess) appear only sporadically on the façade, its basic surface is more complete and the façade has a planar character. On the other hand, if the recesses on the façade predominate, then it loses its surface character and acquires the appearance of a spatial structure. The concept of surface depth occurs between these two extremes, i.e. when the façade has a double character (Fig. 6).

Fig. 6 The concept of surface depth between solidity and structure: ZM 4764, Buenos Aires (Estudio Arqtipo, 2016) (left), Murcia City Hall, Murcia (Rafael Moneo, 1998) (right) (Source: www.archdaily.com)

4. CHARACTERISTIC EXAMPLES

The concept of surface depth is widely used in modern architecture and is present most often in façade surfaces, less often in roofs (fifth façade) and the least often in ceiling surfaces (sixth façade). It is also present in the interior. A characteristic example of surface embossing in terrain topography is shown in traditional forms of underground Chinese villages in Lo-yang and Tungkwan, where the roof plane is united as a whole, while depressed segments of the basic terrain plane appear as randomly arranged atriums (Ching, 2007). A similar concept of surface articulation was applied to the Grand Egyptian Museum Competition in Cairo (Aires Mateus, 2002), where the topography of the natural terrain was imprinted with spontaneously arranged atriums to preserve the surrounding landscape and views of the pyramid complex (Yanguas, Gordo, 2020). (Fig. 7)

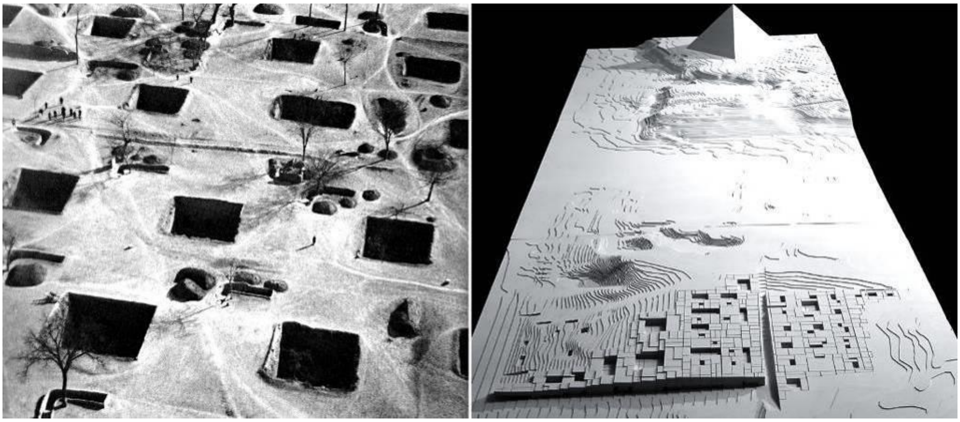

Fig. 7 Underground village in Tungkwan, China (left) and Grand Egyptian Museum Competition, Cairo, Aires Mateus, 2002 (right) (Source: author's archive)

Famous examples where this concept has been applied to façades are Casa del Fascio in Como (arch. Giuseppe Terragni, 1936) and the Palace of Italian Civilization in Rome, (arch. Giovanni Guerrini, arch. Ernesto Bruno La Padula, arch. Mario Romano, 1943). (Fig. 8) At the House of Fascists, the concept of surface depth was applied to the segment of the side façade. The rhythmic order of the windows is connected by horizontal façade strips, in order to preserve the continuity of the surface. A similar principle was used in the design of the façades in “Simply 11” residential complex in Vienna (Delugan Meissl Associated Architects, 2009), with glass loggias used instead of windows. At the Palace of Italian Civilization, by doubling the façade in a retracted plane, a useful in-between space was formed with circular terraces along the external perimeter of the building. The façade of the palace is in a sense reminiscent of the outer wall of the Roman Colosseum.

Fig. 8 Casa del Fascio, Como, Giuseppe Terragni, 1936 (left) and Palace of Italian Civilization, Rome, Giovanni Guerrini, Ernesto Bruno La Padula, Mario Romano, 1943 (right) (Source: author's archive)

The formation of useful in-between space in the double skin façade planes is recognizable in the Building with 86 apartments in Lyon (Eric Lapierre Architecture, 2014) and the villa in Ha Long (VTN Architects, 2020). (Fig. 9) In both cases, between the basic and the retracted façade plane, along with terraces and communications, some living quarters are located. This approach to the design of the building is more complex and demanding, due to the lack of unification of levels, but at the same time, it offers the possibility of synthesizing the concept of surface depth with the functional organization of interior spaces.

Fig. 9 86 Apartments, Lyon, Eric Lapierre Architecture, 2014 (left) and Ha Long Villa, Ha Long, VTN Architects, 2020 (right) (Source: author's archive)

5. Discussion and Conclusion

The concept of surface depth has been increasingly present in architecture in recent decades, although hints of it have been displayed in some examples for centuries. A significant impetus to the development of this concept was the invention of the double skin façade in the middle of the 19th century, when architects began to separate layers of the façade, aiming to improve performance of the building envelope. Since then, numerous variations of the original idea have appeared, grouped in three main directions of thinking, differing in the achieved visual effect - the depth of the surface, and the usefulness of the formed in-between space. The examples presented in this paper aimed to illustrate different starting points and the application of the initial idea.

When the concept of surface depth is applied to a horizontal plane, such as a roof or terrain topography, depressed secondary planes and vertical surfaces that occur along the circumference of the lowered area determine the volume of space, but also create the impression of visual integrity. If the field of imprinted space stands in contrast to the environment of the basic plane, different shape, geometry or orientation can visually strengthen the identity and autonomy of the imprinted field in relation to the wider spatial context. It is important to point out that the effect of surface depth depends to a large extent on the change of the recessed level, which results in a degree of continuity between the recessed field and the elevated area around it. Increasing the depth of the depressed fields weakens their visual relationship with the surrounding surface and strengthens the effect of the volume or structure of the space.

Therefore, if we summarize the observations from the previous analysis, we can conclude the following - in order to say that a façade has depth of surface, it is necessary for it to include three basic characteristics:

a) to be more or less perforated or made of a transparent material;
b) to have the second or more withdrawn plans, or to have a close background behind the base plane; and
c) to have a dual character - surface and spatial, i.e. that its structure is not too decomposed.

The concept of surface depth is not one of the essential concepts in architecture, but its theoretical understanding and practical application provide an opportunity to form visually very attractive pictorial and spatial solutions. This paper aimed to present only some characteristic examples with evidently present the concept of surface depth. Therefore, further research could be directed towards finding, chronologically ordering and analysing other examples in history, paving the way for their more extensive typology and systematization.

Although there is still no explicit consensus in science on the use of the term "surface depth", nor its clear and generally accepted definition, this research hopes to have made some contribution towards its clarification, which can certainly be the basis for further research in this area.

The initial hypothesis that the concept of "surface depth" is achieved by pulling parts of the base surface into one or more secondary spatial planes following the principle of indented relief, where the resulting structure has a dual character - surface and volume, has been confirmed.

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KONCEPT „DUBINE POVRŠINE” U ARHITEKTURI

U istoriji umetnosti i arhitekture, površina je uvek bila nosilac simboličkih i estetskih vrednosti, predmet teorijskih i kritičkih analiza, sa različitim ideološkim, diskurzivnim i filozofskim tumačenjima. Predmet rada u ovom istraživanju su različiti koncepti kompozicije, likovnosti i materijalizacije fasadnih površina, kod kojih je efekat „dubine površine” njihova primarna karakteristika. Analizom potencijala ovog koncepta u artikulaciji strukture fasadnih i drugih površina, konstatovana su tri osnovna pojavna oblika: plastičnost površina (primena sitne fasadne plastike), slojevite fasade sa neiskorišćenim međuprostorom, i sa iskorišćenim međuprostorom. Naučnom analizom referentnih teorijskih izvora i karakterističnih primera, kao i primenom deduktivne metode, istražene su karakteristike koncepta „dubine površine” u arhitekturi, s ciljem sistematizuje principa pomoću kojih se on postiže, mogućnosti njegove primene, kao i načina *uspostavljanja dvojnog karaktera prostornih ravni - površine i volumena. Ovim istraživanjem ostvaren je doprinos u pogledu pojašnjenja ovog koncepta i postavljen je osnov za dalja istraživanja u pravcu pronalaženja, hronologije i analize drugih primera, kako bi se sprovela njihova opsežnija tipologija i sistematizacija.*

Ključne reči: *arhitektura, ekspresija, koncept, dubina površine, dvostruka fasada*

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Original Scientific Paper

TRADITIONAL CIRCULAR PLAN HOUSING FOR RAPIDLY URBANIZING RWANDA

UDC 728.3(675.98)
7.035.9(675.98)

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Abstract. *Rwanda's plots and housing plans featured a circular shape until the time of colonization by Germany and Belgium, when—beginning with the house of Dr Richard Kandth in 1909—a new configuration of buildings and plots having a square or rectangular base was introduced. Today, some of Rwanda's contemporary public buildings seem to recall traditional circular forms, merging local building tradition with the aesthetics of global architecture. With a population of more than 12 million and an annual growth rate of 2.8%, Rwanda aims to accelerate the pace of urbanization by making significant investments in urban infrastructure and the construction sectors of the capital city Kigali and secondary cities. This includes the recent revisiting and development of Rwanda's master plans and the creation of strict guidelines for plots sizes dedicated to individual housing. This paper reconsiders the shapes that may emerge from these frameworks and raise the possibility of a re-emergence of traditional configurations that would reinforce Rwandan identity and transform rapid urbanization into a mechanism of cultural significance. This paper provides an overview of the historical, technical, cultural, and aesthetic values of pre-colonial architectural circular shapes, while also tracing those influences on twenty-first-century public buildings in Kigali and other cities of Rwanda. Authors consider as well how these traditional shapes may potentially be used in housing solutions given the current master plan requirements. Although the circle is not commonly used at present as a plan for single-family housing due to the technical challenges and higher construction costs involved, it nevertheless remains a historically and culturally important design having significant potential for future applications.*

Key words: *circular plans, built heritage, contemporary architecture, Rwanda*

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1. INTRODUCTION

Unlike settlements, in which units are usually grouped, Rwanda’s family units were traditionally spaced apart, and surrounded by planted fields [1]. Such dwellings were typically situated on the tops of hills in areas with minimal slope and could be extended to serve additional functions associated with cattle keeping and artisan workspaces. The size and quality of the hut’s construction varied according to the social level of the owner. While living in circular spaces is foreign to most contemporary dwellers, the central plan has been utilized since the prehistoric times [2], while the arrangement was commonly practiced and well-known in pre-twentieth-century cultures, including Rwanda, which, before its colonization, traditionally used circular plans for housing. This design has been also occasionally utilized in Rwanda's twenty-first-century public building architecture (Figure 1). In this study, authors analyze to what extent circular building forms correspond to a sense of efficiency and assess what contemporary architecture can learn from this design.

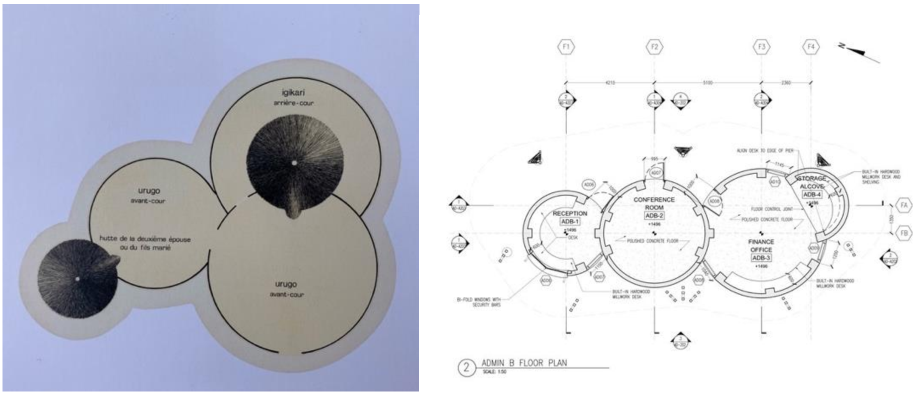

Fig. 1 Traditional habitat of Rwanda with circle plan housing and plots (left) and plan of the Women’s Opportunity Center by Sharon Davis Design built in 2013 (right) © Celestin & Van Pee, 2008: 96; Sharon Davis Design

There are no preserved built structures in Rwanda from the period before 1900 that is, before the colonization period, as Rwandans traditionally used perishable construction materials [1]. After being appointed by Germany as a colonial administrator in Rwanda, in 1909 Richard Kandt began building the new capital, including his own house, which is the oldest remaining built structure in Kigali, Rwanda’s capital [1, 3, 4, 5]. The colonizing powers, first Germany and then Belgium, introduced housing and public buildings with rectangular or square bases, some of which remain today: Maternity Clinic CHUK, Kigali Central Prison, Cloister of the Bernardine Sisters in Kigali, Group Scolaire, Our Lady of Wisdom Cathedral, and the post office in Huye [5], to name a few. After its independence from Belgium in 1962, Rwanda continued to develop the infrastructure in Kigali and other secondary cities following known, previously introduced models.

During the genocide against the Tutsi in 1994, many of the heritage buildings were places in which crimes took place, and many of the buildings were destroyed either during or after the events of the genocide. Following the beginning of the reconciliation process with the new government, a period of urbanization began [6]. Kigali is a rapidly growing city, as exemplified by the dramatic increase in its population from 358,200 in 1996 to 1,630,657 in 2017 [6]. Outside Kigali, there are other rapidly growing towns as well, known as secondary cities, which were established to increase the urbanization rate of Rwanda [7, 8]. The growth of these towns led to a rapid population increase in these areas as more economic opportunities emerged, thus influencing the rural-urban migration.

This urban rebirth process was followed by Vision 2020, Vision 2050, the Economic Development and Poverty Reduction Strategy (I & II), the National Strategy for Transformation (I), master plans, and various other new plans and policies related to green cities and green buildings [5, 7, 8]. As Rwanda was economically progressing, the nation also delved into its traditions and culture to find model buildings appropriate for its future development.

Achieving this goal implies an approach that considers how circular plans may be executable through modern housing architectural techniques. Various factors must be taken into account, including current economic opportunities, local (available) materials, construction technology, energy sustainability, climate factors, exposure to sunshine and protection from rain, sloping terrain, and the unique conditions on the particular plot.

2. METHODOLOGY

In researching for this paper, a combination of materials and methods was utilized. As there are no buildings with a circular plan from the pre-colonial period remaining in Rwanda, the authors visited built heritage sites and pre-colonization period housing replicas at the Ethnographic Museum in Huye to better understand the traditional construction materials, construction elements, the size, and the organization of the inner space of circular building plans. In the course of the research, all of the constructed projects of the XXI century in Rwanda discussed in this paper were visited to make comparisons to globally constructed public buildings with circular plans as well. A document review was also carried out to understand both historical and recent developments in the use of circular plans in Rwandan architecture as well as around the globe. The publications consulted are about the culture of Rwanda and were mainly prepared by the Government of Rwanda and published by its Ethnographic Museum, whereas for the global overview, the authors reviewed relevant academic articles published to date. The focus was on examining circular plans in Rwanda's built heritage and tracking emerging patterns within contemporary architecture in Rwanda, as well as understanding how these patterns follow Rwandan traditions and/or global trends concerning the functions and aesthetics of circular shapes. Additionally, this paper includes the data from two school years of a semester-long course "Architectural Theory" at the University of Rwanda, School of Architecture and Built Environment, in which contemporary architecture in Rwanda was discussed and documented throughout 2018–2020, analyzing global examples (as presented in subchapters 3.1 and 3.3.). Within the course "Architectural Theory", architects working for the Mass Design Group were invited as guest lecturers to better understand their construction practices and the reasoning behind their use of circular forms for public buildings – this information further becomes qualitative data that feeds on the present research. The data collected for this research also includes photographs of buildings in Kigali and other cities taken between 2018–2020.

In this paper, only regular and half circles were analyzed, and one example of an ellipse. For further research, the subject of analysis may include a deformed circle or a combination of a circular base with orthogonal shapes: a circle with a cut-out and/or an add-on circle, an orthogonal base with a truncated circular atrium, and so forth.

3. Theory: Circular Forms throughout History and in Architectural Theory

Traditionally, a circle represents unity, the absolute, and the ideal order, yet, not all circular cities and buildings are cosmograms associated with magic, power and religion [9]. In architecture, forms derived from circular geometry are often thought of as a gesture of "divining the constructed world" [10]. Associated with the divine and the notion of 'perfection', it is no surprise that the circle has also come to symbolize power through a variety of approaches, such as "having the idea of physically arising, constituting centrality, creating a powerful look in the cityscape – nearly all examples are landmarks, gathering and uniting people" [11]. The power of this shape is manifested further when related to magic or religion, guided by mathematical perfection, therefore, acquiring symbolic and sacred purposes in architecture and urban design [12]. Distinctive and well-known examples of integrating the circle into architectural and city design are found as early as in the Greek cities, with the statue of Athena Promachos "asserted the circle of presence of the goddess over the ancient city of Athens" [13], while other examples of cities integrate their planning organization through the shape of a perfect circle, as found in The Round City of Baghdad and the Old City of Shanghai.

A defining property of the circle is that every point on the perimeter lies the same distance from the centre. Nothing is in front of or behind anything else; there is no beginning and no end. Structures designed in this architectural tradition are not only societal and cultural manifestations but are also intended to influence the outer and inner lives of anyone who interacts with them, given the perceptual attention that the shape creates. For example, "a standing stone asserts its circle of presence in the landscape and establishes the place of those who put it there" [14]. The circle taken as a basic, universal geometric shape is an intriguing topic for research in contemporary architectural practice. Given the development of new technologies and materials, circular plans and spheres (i.e. circles in bases and sections) are routinely the subjects of research into new aesthetic ideas in architecture, and their various functions (e.g. integration function, centre/core function, space fluidity, democracy and symbol formation) are commonly discussed.

Historically, circular forms at the global level have been employed throughout entire eras, evident as early as in the early Neolithic era in the Near East, "with simple round monocellular structures" [15]. From ancient Roman times, the Vesta temple, as described by Vitruvius, implements a few circular features such as "a round cella, a circle of columns, and the hemispherical dome of the cella" [13, 15]. Bramante added to the integration of the circle as a distinctive architectural shape through "the way in which the drum and dome project beyond the ring of columns", portraying an ascent of the martyr's soul [15]. Convinced by the power and practicality of the circular geometry, it is not only applied to city organization and representational structures of power but also individual houses, from early times, with round houses seeming to "[dominate] the settlement record from at least the beginning of the 2nd millennium BC" [15]. Looking at Chinese culture, for example, it becomes clear that the round form has been in use there for several thousand years. One example is the tulou ―traditional, circular houses that the Hakka people have been building in Southeast China since the 12th century. These housing complexes, organized around a circular inner courtyard, are built with high clay walls and can accommodate almost 800 people within up to five levels. The circular form endures in many other cultures as well to this day [16, 17]. The nomads of Mongolia, for example, still live in their round yurts.

Circular bases and balls (i.e. circles in bases and sections) are, with the development of new technologies and materials, continuously the subject of research into new aesthetic ideas in architecture that reconsider various program ideas, while they seem to "have a better chance of fitting into the location with low development density or not developed ones […] [with] no clash between the existing orthogonal buildings and a new circle building" [2]. In the following sections, examples of architectural objects of the twenty-first century and several iconic structures from the twentieth century are analyzed in terms of significant aesthetic ideas in which the circle is a key element, where 'aesthetics' go beyond a subjective appreciation of form but are based on parameters that constitute the form as an important perceptual stimulus of i.e. experience, memory, emotion, symbolic function, heritage importance, etc.

Moreover, each aesthetic idea is considered in its entirety, concerning how the space is used, that is, to the program idea, context and materials. Each of the analyzed examples reflects a distinct approach to architectural research and represents a unique spatial-program solution. However, the main goal of this analysis of buildings with circular foundations is to identify topics important for theoretical consideration and which, as such, represent a framework for learning and further application in architecture. Thus, the theoretical potential of aesthetic ideas was the main criterion for selecting the examples included. The following topics have been identified: application of circular foundations to form non-hierarchy architecture; circular bases having the function of emphasizing gathering/integration; circular atriums (circular forms in the negative) to enhance the fluidity of interior space; spiral ramps that enable uninterrupted connection of space vertically to realize various program ideas; spheres and bubbles and the formation of a single inner world; an airy interior "caught" by a ring structure with glass facades, and; irregular circular shapes as part of organic aesthetics. There is no evidence from historical texts or archaeological findings that would elaborate in more detail on the reason why circular shapes were used by the Rwandans to construct their habitat.

3.1. Learning from across the globe: public buildings with circular plan

The 21st Century Museum of Contemporary Art, Kanazawa by SANAA Architects, has a structure of a cylinder with a diameter of 112.5 m and with a glass envelope the height of one floor (ground floor), which is a relatively small height in relation to the diameter [18]. This low cylinder represents a connecting unit in several ways. First of all, the cylinder determines one's first encounter with the museum: While its circular shape clearly defines the boundary of the building, emphasizing the large center dedicated to 21st-century art, its small height and glass envelope make the encounter very welcoming. Secondly, the circle relates equally in all directions to its context, which means that there is no pronounced hierarchy in the classical sense, this being an important theme in SANAA architecture [19]; Thirdly, the cylinder forms the primary medium of communication within the museum, connecting the exterior with the museum's contents, which are located in cubes of higher heights within it. The cylinder offers a view of the context from all sides equally, which with long, arched benches that follow the diameter makes it an ideally protected resting area. Furthermore, the cylinder's circular shape and glass facade are readily understood by visitors, which contributes to easier navigation within the complex space of the museum. In this building, the circular form highlights the building's main conceptual intention, which is to design a park for people to gather and meet, but at the same time, allow them to have access to multiple spatial directions. Here, the circular form "facilitate[s] easy access and a sense of closeness between the building and the city" [20]. Meanwhile, the glass material takes on the role of a reversible membrane where one person 'senses' the other's presence, simultaneously enhancing "a sense of encounter" [20].

The Rolex Learning Center (SANAA) building can be described in terms of a shape having two parallel horizontally-oriented surfaces that are wavy in certain places and contain irregular circular atriums (cylindrical shapes in the negative; i.e. "cut-out"). These atriums, in addition to providing natural lighting and enhanced ventilation, provide through their organic aesthetics the undisturbed fluidity of the interior space. This experience of fluidity and interconnectedness of space is especially important considering the main purpose of the facility: to function as a learning laboratory - an international cultural hub for EPFL that is open to both students and the public. Thus, the aesthetic idea of circular forms is present in the function of the fluidity of space, that is, the program. The circular form here is used to experiment with new and radical ways of interaction, taking advantage of the form to experience views from a variety of levels. On the larger scale and concerning the landscape, the circular shape can minimize the sense of physical boundaries and create a type of artificial geography – "an interior landscape" [21], while on the architectural scale, it reinforces social interaction and learning through the circle's introvert properties.

The first thing one notices in the iconic Solomon R. Guggenheim Museum by Frank Lloyd Wright is the conical structure (inverted truncated cup) that dominates the museum's architectural composition. Although the first impression is of the sculptural quality of this form, Hal Foster emphasizes its essential, integral nature as "formal logic, whitish spiral, as well as program idea, [a] museum as an uninterrupted ramp" [21], which makes this circular interior iconic. Here, the circular form emerges from the continuous logic of the spiral, where the moving force is towards the center, however, objects are placed on the structure's perimetric boundaries, not allowing people to experience the surrounding urban landscape. This building, therefore, highlights the circular form's introvert properties, and its possibilities for an endless type of circulation deriving from the properties of the spiral (Figure 2).

Fig. 2 and 3 Solomon R. Guggenheim Museum by Frank Lloyd Wright in New York City, USA (left) and Reichstag by Foster and Partners in Berlin, Germany (right) © Ilija Gubić, 2010

In contrast, the uninterrupted circular ramp in the glass dome of the Reichstag (New German Parliament) by Foster and Partners, which is also a public space, has a different function: It allows an uninterrupted view of the surrounding space, the city of Berlin. From this vantage, a visual connection with the space occupied by the Assembly Council, located below, is established and "the Bundestag's significance as a democratic forum, an understanding of history, [and] a commitment to public accessibility" [22] is emphasized (Figure 3).

Similarly using the circular shape as an extrovert opportunity for surrounding viewing, Your Rainbow Panorama, artwork by Olafur Eliasson, is a ring structure that was placed on the roof of the ARoS Aarhus Kunstmuseum in Denmark from 2006 to 2011. The small thickness of the ring (approximately 3m) and its rainbow-colored glass façade allowed a view through the walls of the ring (to the visitors moving inside it) from either side of it. This also meant that visitors could view the surrounding city through color filters, allowing for a dynamic view of the very structure of the ring and the colors that overlap. Adding on to this concept, the designers took advantage of the endless properties of the shape, its creation of continuous and uninterrupted movement, and its always changing orientation, creating spaces where one only sees things when moving, and experiencing a variety of different light intensities and spectrums, creating experiential conditions of shifting appearances and constantly renewing relationships between the museum and city.

Exploring the spheres (biosphere) and forming the idea of a specific inner world is a popular topic in architecture in the twenty-first century, often found in coexistence with the concept of ‘Anthropocene’, implying the message that “human activity is having a dominating presence on multiple aspects of the natural world and the functioning of the Earth system, and that this has consequences for how we view and interact with the natural world” [23]. While the emphasis on the shape was first highlighted in architectural design through Buckminster’s Geodesic Dome for the 1967 Montreal exhibition, materializing the aspiration to “make shelter more comfortable and efficient” [24], drawing our attention to the needs of the people, the present-day sphere reference also targets a contemporary triggering issue of climate change and the energy crisis, seeking to allegorically represent the dynamics between human and nature. Consequently, the biosphere calls people to examine their surroundings closely, as that is where living organisms exist, while “no entry of life into the biosphere from cosmic space has ever been observed” [25]. The Amazon Headquarters building in Seattle, designed by American architecture firm NBBJ, for example, is a structure made up of three connected spheres within which the workspace is intertwined with “more than 40,000 plants” [26]. The project is the product of research into the connection between interior space and nature, with the aim of a new, more pleasant work environment.

A unique example of the use of an ellipse in a multi-family residential building is the Zug Schleife by Valerio Olgiati. Its longitudinal façade, which features consoles with ellipses in the negative (cut-out), can be understood once these elliptical forms in the negative are viewed from the interior. That is, behind each ellipse there is a living room. Looking out from the interior of the cube-shaped living room towards the ellipse, the impression is created that the room is in the center. Therefore, the program idea involves experiencing the space from the interior of the apartment such that residents have the impression of being in the small center of each apartment, while the elliptical openings also “generate a sense of distance” [27].

Finally, the base of the Chapel of Reconciliation in Berlin by local architects Rudolf Reitermann and Peter Sassenroth consists of two irregular circular shapes, one inside the other. A space of deceptive width has been created between two shells, of which the outer one is semi-permeable (composed of elegant vertical wooden elements) and serves as a filter. In this way, this interspace together with its envelopes is a connection between the outer world (context) and the inner world of the chapel: a preparation for movement from one world to another. The irregularity of the circular bases makes this transition more spontaneous and organic.

3.2. Examples from Rwanda: public buildings with circular plan

A modern example of the use of circles and circular structures in Rwanda is the Ellen DeGeneres Campus of the Dian Fossey Gorilla Fund, which opened in 2022 (Figure 4), designed by Mass Design Group (MASS). The flat green roofs of the complex are intersected by low circular structures, that is, shallow cylinders with glass cladding that slightly overhang the roof and provide natural lighting to the interior space. Also, these circular structures affect the internal organization of space by forming a center in the open, circular interiors below. Immediately noticeable is that the spatial program solution formed in this way provides natural lighting to the space in the middle. The interior space here is more used compared to classic atriums, and the use of glass is minimal, which is important for Rwanda (given the limited availability of glass).

Fig. 4 Ellen DeGeneres Campus of the Dian Fossey Gorilla Fund by MASS Design in Musanze, Rwanda © Iwan Baan, 2021

The Rwanda Institute for Conservation is a new campus designed by Mass Design Group (MASS) in Bugesera, Rwanda. The primary guiding concept for the RICA campus was the creation of a so-called “one health" space, which refers to the integration of humans, animals and plants in one space as a single element. Through this approach, MASS transformed the previously existing conditions of degraded soil, food insecurity and deforestation into a "one health" design promoting environmental, human and animal wellness. Through a climate-smart design, MASS is using locally available materials and incorporating passive design systems. Circulation throughout the spaces has been created to promote different flexibility. In addition, the design approach aims to reduce the embodied energy of the building through better integration of space and through the building materials used, namely, wood, rammed earth and reinforced concrete. Passive lighting and ventilation systems have also been incorporated as an example of sustainable architecture. Perforations along the north-south side are meant to improve the ventilation of the building. In addition, the use of large windows and clear glass optimizes daylight. Cross ventilation and stack ventilation through the dining and sleeping rooms were also integrated into the design, and long, vertical wooden slats are integrated into the space to ventilate the corridors and bathrooms. In addition, clerestory windows have been used to create more lighting in the building and ventilate the space even further.

Kigali Convention Complex comprises Kigali Convention Centre and Radisson Blu Hotel, designed by German architect Roland Dieterle. The complex spans over 13 hectares on 80,000 m^2. The landmark Kigali Convention Centre (KCC) is shaped like a dome, which has special significance in traditional Rwandan architecture: By use of the dome, the architect refers to the King's palace in Nyanza (which is also dome-shaped) and has adopted traditional construction technologies but with modern materials, resulting in a steel structured dome (Figure 5). The KCC has 17 function rooms and an auditorium, with its unique design integrating the culture and traditions of Africa into the facilities and their functional technology. The first and largest convention centre in the region, with a capacity of 2600 guests, the KCC is the leading destination for large events in Rwanda.

Fig. 5 Kigali Convention Centre and Radisson Blu Hotel by Roland Dieterle in Kigali, Rwanda © Emmanuel Kanmugire, 2016

Designed by Sharon Davis, the Women's Opportunity Centre (Figure 6) is a village-like series of low-rise pavilions serving as classrooms and arranged in a circular pattern at the heart of the Kayonza site in the eastern region of Rwanda. The project aims to design a safe public space for over 3000 women and girls so as to promote their social and economic development within the context of the local Rwandan culture using available natural materials [5]. A farmers' market, a community space, gardens, and guest lodgings are all arranged along the outer edges of the circle. The design revives a lost Rwandan design tradition, as its main idea is derived from vernacular Rwandan villages. The buildings have round shapes, perforated brick walls, and hanging roofs, thus allowing passive cooling and natural ventilation.

Fig. 6 Women's Opportunity Center © Elizabeth Felicella

The Gahanga Cricket Stadium designed by Light Earth Designs is the home of Rwandan cricket. It was constructed to promote reconciliation through sports after the 1994 genocide against Tutsis. The stadium is a sustainable project which used local materials to promote carbon savings. The roofs of the primary stadium enclosure utilize the tile-vaulting technique of compressed soil-cement tiles. In appearance, these vaulted roofs imitate both the Rwandan hilly landscape and a bouncing ball's trajectory. The vaults are made with a thin shell layer of tiles laid on a temporary timber skeleton that spans up to 16m. A waterproof layer is then added, followed by small chunks of local granite, which increase the stability of the structure by adding weight. Perforated brick walls were used to mark the spaces and allow lighting and ventilation. The banking creates a wonderful natural amphitheater with great views of the pitch and wetland valley beyond.

Bisate Lodge is one of the eco-retreat lodges located in the northern region of Rwanda. The site is characterized as a "natural amphitheater of an eroded volcanic cone". The lodge itself is a contemporary architectural response in the form of an alternative stimulus of a primordial volcanic landscape, as explained by Nicholas Plewman, architect of the project. The project features six villa units with spherical, thatched structures that imitate the topography of Rwanda. The villa is warmed by a central fireplace with a private viewing deck overlooking Mount Bisoke. The architectural inspiration for the lodge came from the layout of a traditional royal palace, and the interiors are decorated with Rwandan arts and cultural items. The project used local materials such as colorful textiles and other artefacts to decorate the spaces, with construction materials consisting of concrete, steel, timber, synthetic thatch, lava stones, natural granite, bamboo, reed and papyrus.

As indicated by the above descriptions, public buildings with circle forms in Rwanda are generally inspired by the Rwandan traditional building layout and mountainous topography. This can be explained as creating a "syntax of perceptual security" in the contemporary space of the people, inspired by the surrounding landscape, and expressed through people's reliance "towards pure compositions and […] faithfulness towards 'schemata' (pure forms)" [28]. Consequently, the inspiration for shape formation is not only a matter of traditional arrangement based on the continuation of habit, but seems to have deeper justifications on perhaps on-situ arrangements that consider a "wider urban landscape configuration" and a sensitivity towards "green objects" that play a role in compositional gestures [29].

3.3. Learning from across the globe: Single family housing with circular plan

A well-known and documented example of a single-family house with a circular base is the iconic Melnikov House by Konstantin Melnikov, located in Moscow, Russia. This is a classic residence with an aesthetic different from other traditional Soviet residential architecture. The concept of the house evolves from two interlocking cylindrical volumes that stand at a height of three stories, with the capacity to accommodate all the spaces needed for family and work [2, 30, 31]. The architect's reasoning differs for the two cylinders. The first cylinder was put at a lower height than the second one, which faces the street with a glazed curtain wall that includes the entry of the house. In the rear, the façade is constructed in a honeycomb latticework using local bricks, resulting in a rigid structure with numerous hexagonal windows to light the interior part of the house and resulting in a unique aesthetic for the rear cylinder. The walls of the cylinders are the sole load bearers, leaving the interior spaces free. The kitchen and bathroom are located on the main floor, with a winding staircase going to the first floor, which contains the bedrooms and living rooms. Another unique aspect of this building is the use of staircases, with a spiral one rising from the family spaces on the first floor to reach a double-height studio and roof terrace. The whole house is designed with a quasi-open plan (with partial walls separating the bedrooms) to allow sunlight to soak the interior through the continuous glazed walls of the cylinder.

The Casa Rotonda by Mario Botta is another example of a single-family house with a circular plan. Located in Ticino, Switzerland, this cylindrical house was developed on four levels to avoid any comparison to neighboring buildings, while connecting with the distant landscape and the horizon. South of the house, the skylight is linked to two large side openings that serve to connect its interior and exterior. On the other side, to the north, a set of staircases rise like a column interrupting the continuous wall of the cylinder. The four floors of the house have mostly open plans with few separation walls, emphasizing the continuity of the space and at the same time allowing the natural light to amply flow over the interior spaces. The house is subdivided to handle the different functions of life: The basement is reserved for technical and service use, the ground floor acts as a transition between inside and outside and contains the entrance and the portico, the first-floor functions as the day area and contains the living areas arranged in an open and continuous space, while the second floor contains the sleeping areas with some separation walls.

Lastly, the Round Beach House in St Andrews, Australia, designed by Austin Maynard Architects, is another family house that was developed on a circular base. This unique beach house was conceived to eliminate any dominant orientation: having no front, back or sides, it instead features a continuous façade where all sides are equally important. In the interior, the round floor plan reflects a desire to remove the corridor, a banal link between rooms that seems to be an underused space. In this beach house, all the rooms are open to each other with no fixed separation walls and with a central staircase that provides a vertical link but occupies minimum space. This central stairwell is well-lit to openly amplify the depth of the small rooms while at the same time providing a visual link between them. The ground floor plan is divided into sections from the perimeter to the center, allocating various functions such living room, dining room, kitchen, bathroom, and laundry room, all taking up minimal yet sufficient space. The first floor, with the free arrangement of sleeping spaces, is entirely open except for the bathrooms. Another interesting aspect of this house is its entrance, which is formed by a covered double-high open space extended from the living room inside the cylindrical volume, which acts as a boundary between the inside and the outside.

4. Discussion & Conclusion

The use of the circle in the foundations of single-family housing is uncommon due to "design difficulties, technological difficulties as well as construction costs" [2], but it is important nonetheless. Since the traditional residential architecture of Rwanda is based on a circular foundation and this tradition has not been interrupted so far in the past, the authors wanted to explore to what extent the use of traditional circular bases is optimal at the present moment. As noted earlier, this required an approach that examines how circular plans may be executable through modern housing architectural techniques in a way that fits with the life habits of contemporary Rwandans and that is at the same time aesthetically pleasing. Among the factors that must be taken into account are current economic opportunities, local (available) materials, the use of sometimes low-tech construction technology, energy sustainability, climate factors, exposure to sunshine and protection from rain, the prevalence of sloping terrain, and the unique conditions on the particular plot.

Concerning aesthetics, the "gathering" effect of a circular foundation, namely, that the building is provided with a common core or center, with equal treatment of the periphery on all sides, can in principle be applied in contemporary Rwandan single-family residential architecture. In context, however, it should be taken into account that large glass facades increase the price of construction, and in Rwanda, where glass is not easily accessible, alternative means of allowing light to permeate the interiors of circular houses may need to be explored.

Regarding the utilization of space in a house with a circular base, especially when the size of the plot is limited, the concept of "cheese" architecture or multiple circular atriums (such as used at the Rolex Learning Center) for single-family homes is not directly applicable unless they are relatively large. The aesthetic idea of fluidity is more strongly experienced when the space is larger, according to an analysis conducted in the research of 24 objects, with "circle in [a] circle" being the least represented [2]. According to the case study in question, a circular base with an orthogonal division was the most common, followed by the radial division [2].

Based on these considerations, we analyzed the following shapes: circle with orthogonal division, radial organization with center function, radial organization circle with atrium, several circles in the given parameters of plots having 300 m^2 and the possibility to construct 50% of the plot. In addition, important to consider is the slope of the terrain of 30%.

Housing culture, that is, life habits and how these affect the internal organization of a building, must feature in the conclusions one reaches about what is feasible. For example, orthogonal furniture is harder to place in a circular room [31]. The authors pose a series of questions to better understand Rwandan culture and habits, for example: Do they need a covered space to be shielded from the effects of rain and sun? (Although the latter question is not among the traditional practices, it might yet be the case because Rwanda has extended rainy periods). Concerns of such nature further illustrate how climatic conditions can shape the way space is used.

The issue of energy use and local materials is also relevant. On the one hand, the circle reduces the relevance of the construction material because the coverage volume is smaller, and this is emphasized as a positive [31]. Stone coverings on the circular facade are expensive, or formwork is more expensive if concrete is used. There is also the question of the price of a roof over a circular foundation: Does the circular shape increase the price, and is the roof made of tile or metal?

Another issue is upgrading. In case new circular structures are added to the existing ones, this requires more materials and more facades that are not energy efficient [29]. On the other hand, adding a circle has the advantage of allowing for phased construction, so not everything has to be built at once.

Also, there is the question of the originality of the author's concrete solution of applying the circle in a more abstract creative way: This is an important issue that depends on the design preferences of clients (e.g. Oligiati Atelier Bardill introduced a circular geometry that was not intended to be adapted to the plot, i.e. the context, but opens inward so that the circle provides centricity).

The question of optimality, then, hinges on the ratio of price, spatial quality, and materials. Is luxury required, or can we achieve the same effect with modest construction technologies?

Given the master plan that was adopted in 2020, according to which the challenge of urbanization is seen as being solved by limiting single-family housing construction, we investigated whether circular forms would be suitable for the housing given the new master plan requirements. The new zoning regulations for single-family houses allow for a maximum plot of 500 m^2 with 40% of maximum building coverage and 0.5 maximum floor area ratio. The regulations also allow for G + 1 + P, where the roof pitch shell is less than 30%. This research might guide researchers and practitioners to further explore possibility to build housing with circle base, optimizing scarce resources.

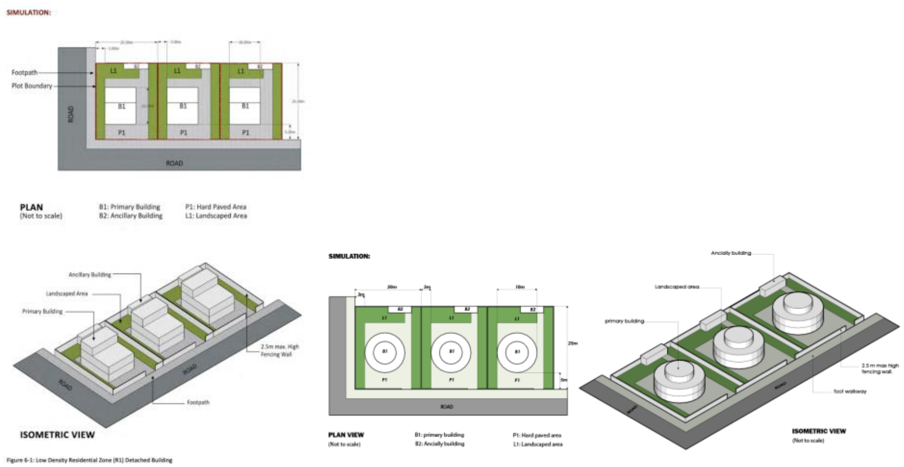

Fig. 7 Simulation prepared by the Government of Rwanda illustrating master plan R1 (left) and the alternative simulation of circle base building, prepared by authors (right).

In designing a circular house, it is incumbent upon the architect to define its spatial organization. The absence of fixed, solid walls, for example, offers more room for flexibility and simplifies subsequent adaptation and reconfiguration of the structure's interior. Indeed, it is not only the interior which opens up new possibilities when conceived of as round—the particular stability of such houses and the enhanced insulation against wind and cold make a circular design especially sensible. The construction of circular houses requires fewer materials than rectangular ones of the same floor area because, mathematically speaking, round figures possess the most favorable ratio of base to the lateral surface area. Yet another advantage of a circular house is the fact that both energy loss and materials input is 13% lower on average than in even the best-built rectangular houses. When temperatures drop, one benefits not only from the superior insulation but also from increased sun exposure: In winter, the sun is lower on the horizon, shines into the building and warms the interior. By contrast, because of the sun's higher angle in the summer sky, it barely shines into the building, thereby heating it less. And in addition, the large, flat roof offers the possibility of installing solar panels to efficiently utilize the sun's energy.

This research contributes to the knowledge fund on buildings with circular plan, with both public and private functions, that would further guide researchers and practitioners interested in the theme. In addition, paper uses Rwanda as a case study, contributing to the very limited academic production on architecture in East Africa.

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TRADICIONALNA JEDNOPORODIČNA STAMBENA ARHITEKTURA KRUŽNOG PLANA ZA SAVREMENO STANOVANJE URBANIZUJUĆE RUANDE?

Dok je tradicionalno oblik parcele i stambenog prostora bio krug u Ruandi, kolonijalne sile su, Nemačka pa Belgija, počevši od kuće dr Ridžarda Kandta iz 1909. godine, počeli da grade zgrade i parcelišu zemlju sa kvadratnom ili pravougaonom osnovom. U nekim slučajevima, savremena arhitektura HHI veka javnih zgrada u Ruandi crpi inspiraciju iz tradicionalnih kružnih formi, i prevodi tradiciju u estetiku od globalnog arhitektonskog značaja. Danas, sa populacijom od više od 12 miliona, sa projekcijama na 24 miliona do 2050. godine, Ruanda ima za cilj da ubrza svoju stopu urbanizacije značajnim ulaganjima u infrastrukturu i građevinski fond glavnog grada Kigalija i manjih pograničnih gradova. Ruanda je nedavno izradila nove urbane planove dajući stroge smernice o veličinama parcela za individualno stanovanje. Ovaj rad pruža pregled istorijskih, tehničkih, kulturnih i estetskih vrednosti oblika prekolonijalne arhitekture i prati te uticaje na javne zgrade danas, i proučava da li se takvi oblici mogu koristiti za jednoporodično stanovanje po zadatim uslovima iz urbanih planova. Upotreba kruga u osnovi jednoporodičnog stanovanja nije uobičajena zbog tehnoloških poteškoća, kao i troškova izgradnje, te je kontinuitet tradicioalne forme teško preporučljiv za savremeno stanovanje u Ruandi, imajući u vidu zavisnost od uvoznih materijala, i pretežno siromašnpro stanovništvo.

Ključne reči: *kružne forme, graditeljsko nasleđe, savremena arhitektura, Ruanda*

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MINIMALISM IN ARCHITECTURE: A BASIS FOR RESOURCE CONSERVATION AND SUSTAINABLE DEVELOPMENT

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Abstract. *In a novel way, modern architecture has a great influence and impact on present-day contemporary architecture. Since the late 1980s, 'minimalism in architecture has been taken into consideration. Less is more is emphasized, which adheres to the philosophy of filling the space with the necessary items and clearing unneeded clutter to allow room for significant materials and objects. With simple shapes and clear lines, a neutral color scheme, and plain textures, minimalism exudes calm. Minimalism is about eliminating life's excesses. We can find freedom, contentment, and the ability to concentrate on what matters most. Whether it was during the sustainable era or in the twenty-first century, minimalism is adopting the conventional "less is more" way of life. In addition to displaying a wide range of hues, architecture is a form of art. Iranian architecture embodies historical grandeur and devotion, a commitment to religious education, and a rejection of materialism. It is a product of Islamic civilization. However, recycling well-known architectural features like minarets, courtyards, and mashrabiya frequently runs afoul of modern trends in architecture, which are not necessarily opposed to the fundamentals of Islamic architecture. Minimalism is regarded as a fundamental resource and an alternative to the present standard aesthetic. In order to draw designers with sustainable goals' attention to the relationships between minimalism and sustainability, the following questions are briefly addressed in this paper. How does minimalist design work? What does minimalist design entail? Is the minimalist style the best style for environmentally friendly architecture? This paper tries to attempt to examine a minimalist aesthetic for sustainable building and design. This paper discusses a comprehensive overview and analysis of minimalism and its guiding principles in architecture. It also continues by outlining the features and minimalistic foundations of Islamic architecture.*

Key words: *Minimalism, Minimalist Architecture, Simplicity, Sustainable Development, Environmental Sustainability, Resource Conservation*

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1. INTRODUCTION

The idea of minimalism is currently popular in nations with luxury and strong consumer cultures, such as Japan, the USA, and numerous post-socialist nations in Europe [1]. As minimalism has gained popularity, it has evolved in a few different ways. While some minimalists focus more on aesthetics, others combine the ideas of simplicity with sustainability and environmental concerns [2] [3]. Although the structures now under development may seem lovely, Sugimoto believes that true beauty is defined by "the power to transcend physical form" and "the depth of meaning generated from inspiration" [4]. A new aesthetic for a design that takes sustainability into account is necessary.

The responses, which were needed and based on a thorough review of the literature, were meant to clarify the interconnected relationships between the minimalist aesthetic, the core of Islamic architecture, sustainable design, and the possibility of their coexistence. The guiding principles of minimalism and sustainability are important to examine as the ultimate answer to the pressing humanitarian and environmental crises the world is facing today. Minimalism might provide sustainability, an emergent design trend, the appropriate aesthetics, a face, as well as a background and legacy. To increase the quality of life, the minimalist style shift begins with decluttering and resource reduction. Many people who practice voluntary simplicity believe that "it is the 'kind of possessions' that matters most and the 'attitude' toward them, 'not the number'" [5]; yet, for minimalists, the main aim is to have fewer goods and "get rid of anything that's unneeded" [6].

2. RESEARCH METHODOLOGY

In this paper, the qualitative research method has been used. The systematic literature review has been explored through the internet and secondary data from relevant published academic literature from journal articles and research papers. The research technique is focused on demonstrating unequal desires and distribution that can compete for a qualitative literature evaluation related to the primary issues, such as resource conservation, sustainability and environmental design. The data collected in the qualitative research is the data that comes from a number of researches that are described descriptively and qualitatively, which are supported by illustrations and photographs to reinforce the arguments put forward. The basic concepts and backgrounds are investigated through literature and on-line media; an observation to work for the qualitative analysis is conducted to document and explain the minimalist understandings of architecture, building construction and resource conservation. Finally the SWOT analysis is conducted for the application of Minimalism in Architecture with reference to environmental design.

3. MINIMALISM: THE STUDY CONTEXT

The reduction of a subject to its essential elements is referred to as minimalism [7]. Along with fashion, music, and decoration, minimalism is now a term used to describe the use of clean, simple lines, and the elimination of idiomatic features, and, in the case of architecture, the examination of the use of space and the potential for construction [8]. The attention to fundamental components like light and how it interacts with the masses and volumes that make up buildings to define space, design, and structure is what defines minimalism in architecture. The pursuit of simplicity is seen as a path to personal freedom [9]. In terms of art history, the 1960s and 1970s sculpture movement is known as minimalism. In terms of aesthetics, functionalism and international style based on Mies Van der Rohe's maxim "less is more" are frequently linked to it in architecture [10]. The second meaning of minimalism is connected to Herbert Spencer's minimax theory from the 19th century [10]. The biological idea of trying to get the most out of the least amount of energy formed the foundation for this notion.

Three different versions of minimalism are applied at the Institute of Ecological and Experimental Architecture [10]. The first interpretation: minimalism in spatial differentiation presents the idea of a home with an open-plan living area that is flexible in its user's interpretation and is accompanied by reliable technological and sanitary services. The second method examines aesthetic minimalism, which is centered on using the fewest possible elements to have the greatest possible visual impact. The third strategy's fundamental tenet, that is to reduce the environmental impact, among other things by minimizing resources. The strategy that reflects minimalism and the associated idea of intentional simplicity is referred to as lean. The purpose of this investigation is to highlight architectural minimalism as the greatest method for implementing solar renewable energy and energy efficiency in our environment.

3.1. Minimalism: A Simple Design Philosophy

The idea of minimalism is to make things simpler by stripping them down to their simplest forms. The idea is to remove as little clutter as possible, to the point where no more elements, features, or joinery can be eliminated to improve the design-not that decoration should be entirely gone [7]. Moreover, a minimalistic design style is characterized by austerity, reductionism, simple forms, and a colour scheme in only one colour [11] [12].

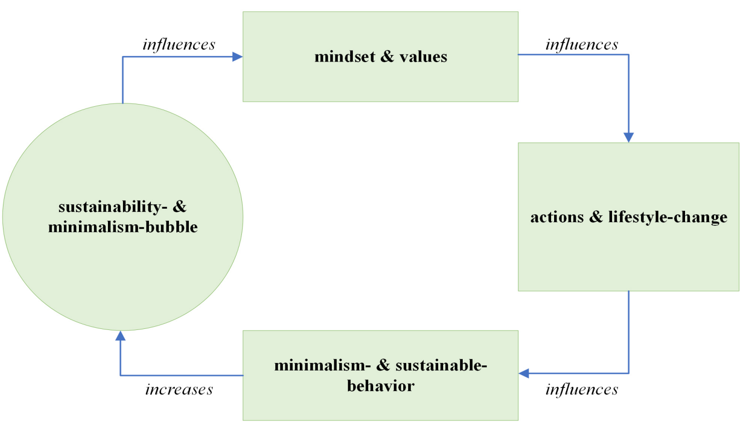

Fig. 1 Visualization of the 'Minimalism Process' (Source: http://hj.diva-portal.org/smash/get/diva2:1674601/FULLTEXT01.pdf)

To accomplish this, it is crucial to make use of vacant space. These materials typically have neutral colours that complement minimalist designs, which helps to keep the designs' core as simple as possible and eliminate any pointless decoration [7]. When the arts and crafts movement gained popularity in Britain in the late 19th century, people appreciated the attitude of "truth to materials" with attention to the profound and inherent characteristics of materials. Minimalist designers respectfully "listen to figure," recognizing the good aspects in basic and commonplace materials, in their pursuit of essence and simplicity [7].

3.2. Simplicity as a Historical Development of Minimalistic Design

Although the concept of minimalism feels fresh, its roots and guiding principles have a long history. Seneca said, "It is not the guy who has too little but the man who seeks more, that is poor," in 1st BCE, when the concept of simple living first appeared. Living simply and without greed is about fulfilling your own purpose, not that of others, according to Christianity. Islam discusses "Zuhd," which is asceticism. It encourages moderation and discourages excess or extremism in all facets of life. It encourages individuals to meet their fundamental requirements sparingly and without squandering any resources. Sanyasa, a Hindu concept, refers to a modest existence with few or no material things [13]. The social and creative conditions that arose in response to the Industrial Revolution are where the idea of minimalism first evolved in the West. People have come to the realization that they were overspending on goods. A movement known as "Minimalism" that was spurred on by a 1965 work by Richard Wollheim gave birth to the style [14]. Japanese Zen philosophy served as an inspiration for the minimalist movement. However, Japan is returning to its traditional minimalist ways in the twenty-first century [15]. The art world reflects the public's anxiety, reflection, and opposition to civilization and earlier trends in artistic thought. Minimalism looked to be a violation of the typical aesthetic attitude in this setting. The style got its origins as a response to Abstract Expressionism, which was known for using abstract color, markings, and gestures to express or evoke feelings from people's inner worlds [16]. The minimalist trend might perhaps be best described at the time as a different style of expression that engaged the mind more than the emotions. By "removing the appearance of composition," minimalism sought to "present the original shape of things to the spectator" [16].

Minimalism was first promoted and claimed in the disciplines of art, mainly painting and sculpture. At the time, minimalism aimed to make paintings simpler by reducing colors and figures while eschewing embellishments that would interfere with the main idea or effect [17]. In an effort to exclude any external meaning from his paintings, Frank Stella restricted his work to geometric forms, a style popularised by Donald Judd. The height of artistic minimalism was in the late 1960s and early 1970s. In the later 1980s, minimalism emerged as a widely popular and significant design trend. As a result, minimalism rapidly grew in popularity and encouraged designers to employ fewer materials, clean surfaces, and simple designs [17]. The ancient Greek school of philosophy known as Stoicism makes reference to minimalism. One of the basic tenets of the Stoics is learning to thoroughly appreciate and be grateful for the things we already have in order to lessen our need for more [18]. Peter Walker's use of minimalism in landscape design is unique and inventive, minimalist gardens may also be commemorative in addition to their use of materials, geometric shapes, and plant arrangement [19].

People began to understand the serious consequences of ignoring environmental and renewable energy challenges in the 1990s. Overuse of natural resources hindered human growth, which led to the awareness that Minimalism needed to exist and develop. Back to basics, a catchphrase popular at the period, refers to people's desire to get back to the essentials and restore objects to their original state [17]. Today, minimalist design is used in many other fields, such as web design, industrial design, product design, even food design, among others. Different fields' minimalist designers use their own rules and standards to apply minimalism to their works. However, there is insufficient evidence to suggest that minimalism and ecological design are directly related. An original way of considering different methods of minimal design is to compare and combine a number of minimalism's tenets with those found in ecological design.

4. PRINCIPLES GOVERNING MINIMALISM

Diverse disciplines of application for minimalist design often have different guiding concepts, producing various created works. It is insufficient to employ only principles from one specific field to represent or explain minimalism in general, even when these differentiated ideas have their roots in the same historical background. Although there are many different notions of "reduction" in use, the following criteria consistently apply: "minimality of methods," "minimality of meaning," "minimality of structure," and "usage of patterns". When simplicity is established as a goal, "minimalism is not to be equated with simplicity," but rather with a collection of values that "go to extremes to generate a focus of the recipient, a participation of the user, and a way of looking at things - a minimal perspective [20]. “Rigid concentrating through the elimination of distraction" produces minimalist simplicity [21]. The idea of essence, or "what is left when there is nothing else that you can throw away," influences minimalism's final product. Because minimalism is an "open idea," it

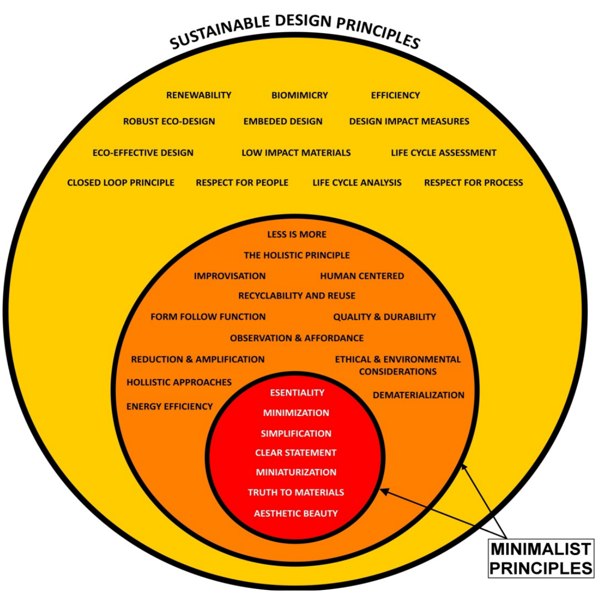

Fig. 2 The principles of minimalism and sustainability (Source: https://actatechicanapocensis.com)

is challenging to pin down its exact historical origins [22]. It is a phenomenon with historical roots [23]. The maxim "less is more" is regarded as the minimalist aesthetics' "working" concept [24]. It might be viewed as the core principle of minimalism.

The pursuit of "expressive" clarity has its roots in minimalism's "propensity towards literalness," according to Colpitt [21]. By "finding profound experience in ordinary experience," minimalism reorganizes values. Minimalist design "makes a clear message about the nature of reality" by shifting the focus to direct experience. In light of this research, the following summary of minimalist design concepts (Figure 2).

4.1. Simplicity: Eliminating Excessive Decoration

One of the main principles of minimalism is the removal of pointless decorative elements from designs. When there is too much substance and adornment, not only does the main theme or point become muddled, but there is also a waste of resources in terms of resources, space, and labor. Beyond aesthetics, simplicity includes a moral component that can be understood as reflecting an innate characteristic or the quest for philosophical or literary insight into the nature of harmony, reason, and truth. The well-known phrase "less is more," attributed to the German architect Ludwig Mies van der Rohe [7], effectively captures this idea. Using minimal elements to achieve maximized function is what this phase might be interpreted to mean [17]. For instance, compile the fundamental components required for a structure to function and arrange them according to a straightforward architectural form. Although the architecture may appear straightforward, its functions are maintained—perhaps even more so than in a typical building—because its components are well-organized, perform a variety of tasks, or make use of cutting-edge technology. A floor's functionality is maximized and additional heating equipment can be saved if it is made to have electric heating capabilities beyond those of regular floors. Less is more does not only refer to these examples; rather, it reflects the idea that in minimalist design, only the aspects that are absolutely necessary are kept.

4.2. Miniaturization: Reducing the Size

Miniaturization, the minimalist project's guiding philosophy is minimalism, which "converges around the notion of decreasing" [21]. Functional significance of reduction The Braun television, the Atelier TV 3, which appears to be made entirely of the screen, and the Apple iMac all have reduced designs in black and white [25]. Equally significant is the idea of "amplification," which "generates a theoretical dilemma" in those minimalists" expect to accomplish an amplification of effect through a reduction of means" [21]. According to Leepa, "limiting the number of integers that make up a work of design permits a concentration on the remaining elements, investing them more strongly and immediately with the kinds of effects they intend to accomplish. The form is influenced by the technical characteristics of a product's components. Smaller components enabled the creation of new goods. The ability of the technology has been translated into form by the trend toward miniaturization. A drastic reduction in product size, for instance, was made feasible by the introduction of transistors in the 1950s and the microchip in the 1980s.

4.3. Dematerialization

The idea of "a product of service" relates to the presumption that products will be reconceived as "services" as opposed to being something that "consumers" "buy, possess, and dispose of" [26]. Design trends that dematerialize are influenced by a variety of things, including technological advancements, the new economy, environmental consciousness, social motivations, frustration with the abundance of goods and visual stimulation in our culture, and criticism of our overdesigned surroundings. Mart Guixé is a prime example of a functionally-focused designer in this regard: "I've been striving to erase the object's form and to build it as if it were pure function" [27]. Sasaki believes that Fukasawa frequently employs the phrase "creating the unconscious," which "summons up the idea of establishing a basic awareness" [28]. For instance, a frameless display called LED Watch (2001) for DMN + IDEO was created as a "white cube fashioned like a watch." I thought that the display's contents, not the windows that surrounded it, were what mattered. Electronic gadgets could only appear as electronic devices because of this display window [29]. Even if the end outcome is different, the instinctual knowledge of how to utilize something can be suggested in a design, most frequently through shape, but also through memory and experience of previous items that appeared or behaved similarly [30].

4.4. Materials: Truth to Materials

The use of the material has played a crucial role in minimalist design, particularly in the fields of architecture, industrial design, interior design, and other design disciplines. Geometry, the natural world, and real materials are all incorporated into Tadao Ando's architectural designs, whereas Takashi Sugimoto creates "a layered discontinuity that seems to evoke an ancient spirit" [4]. German architect Mies van der Rohe, who is credited with creating minimalist architecture [31], constructed the buildings using newly developed materials for his time (around 1950), such as steel and glass panels. Like Sullivan's maxim, the notion that form should respect the properties of the material from which it is derived has long been a cornerstone of Western design thought. Popularized with the phrase "truth to materials," which was paraphrased from John Ruskin's writings [32]. Texture, hardness, elasticity, and other properties vary depending on the substance. Some technical issues that cannot be solved or can only be solved partially without the right materials might be able to be solved with them. The use of materials is in keeping with the concepts of simplicity and purity since landscape minimalist designers tend to employ "contemporary materials with few decorative features" [19] such as stainless steel, glasses, wood, and rocks to express its core appearance. Despite the materials' lack of aesthetic details, designers were nonetheless able to create a variety of settings by rearranging and repeating them [33]. "Materials can express a feeling of history, a link to a person or place," according to Super Potato. Sugimoto views his designs as "a delicate network of information, delivered through varied materials" and believes that "materials provide information".

4.5. Empty: the Vital Element

In minimalist design, being empty does not mean nothing; in fact, it gives the design more options. This is the antithesis of excessive adornment. A particular quantity of white space emphasizes how distinct the main subject is in comparison to other aspects while discouraging focus or/and attention disruptions. Empty space is referred to as "freedom of movement" in

Japanese gardens, but it may also be seen as offering more conceptual options and greater functional flexibility for growth or movement [31]. A wall with fewer decorations and more empty space gives "visual breathing room," according to a frequently used concept in interior design [34]. A smaller amount of furniture in an apartment gives residents more freedom to select their own paths, activities, maintenance etc.

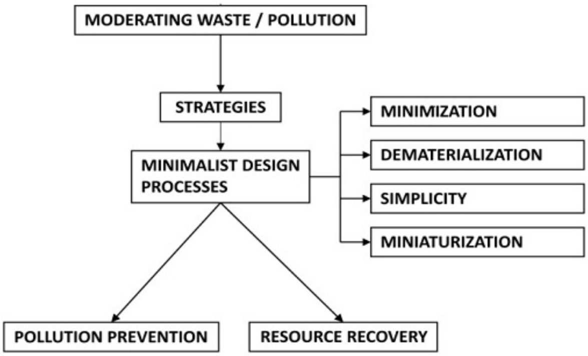

Fig. 3 Minimalist process considering sustainability (Source: https://actatechicanapocensis.com)

5. Materialism: Empirical Methods and an Analytical Strategy

Although there are many different definitions of materialism, they all share the idea that material goods are a fundamental part of materialists' lives and are seen as the main sources of happiness and success [35]. The empirical evidence included in this study has repeatedly demonstrated a bad correlation between materialism and life satisfaction as well as in certain areas of life, like standard of living, family, and leisure [36] [37] [38]. Given the possibility that minimalists would not value materialism, these findings have consequences for the ongoing study. The amount of consumerism in the American setting may be high [39] [40], but the minimalist message is becoming more popular worldwide, particularly in post-socialist economic and political environments [41]. The link between materialism and happiness has been the subject of several explanations [42].

This study was created using a descriptive-analytical methodology based on the most recent literature on current concerns in architecture and design. Studying the idea and goals of sustainable architecture as well as the rules and requirements for eco-friendly, minimalist interior design the maintenance of the four resources-human, environmental, social, and economic is referred to as sustainability.

- The growth of human abilities and capacity to support and develop societies is what is meant by human sustainability.
- The term "social sustainability" refers to sustaining and enhancing the social quality of relationships between people as well as protecting resources for future generations.
- In terms of economic sustainability, it seeks to raise living standards and promote social equality.
- Environmental sustainability is increasing personal well-being as a result by protecting natural resources without endangering their ability to meet present-day requirements [43].

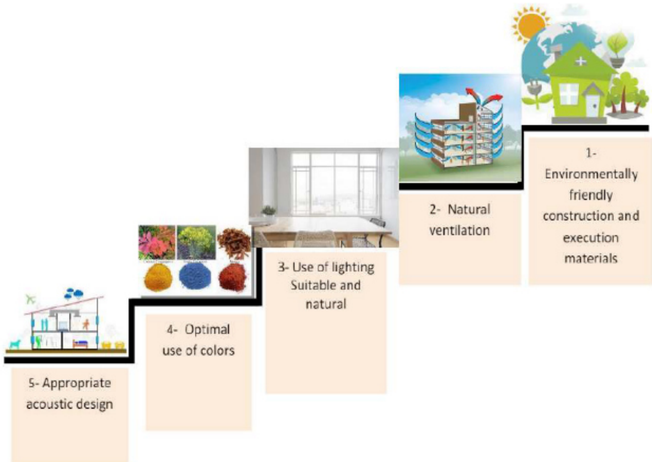

Fig. 4 Specification of green buildings (Source: https://gercj.com)

Sustainable design, it aims to create environments that are healthier and more nourishing for people while also taking into account how well nature can provide for the rest of the animals and future generations [44]. Since nature is a source of health and nutrition, sustainable development is based on environmental awareness. Building spaces responsibly for the environment involves reducing emissions that harm the environment, moving toward the use of recyclable materials that are good for the environment, switching to renewable energy sources, cutting down on energy waste, and operating spaces with environmental controls that make the environment more comfortable while reducing damage (Figure 4). On both users and the environment, as well as on the effectiveness of water use [45]. Sustainable architecture is the design and construction of green structures in accordance with the principles of sustainable development, such as limiting the use of ecologically damaging materials to lower construction and operating costs, improve user health, and boost productivity [46].

Given the aforementioned materialism findings and the somewhat scant research on low-consumption lifestyles, it is crucial to examine the experiences, traits, attitudes, and behaviours of people who identify as minimalists in order to start understanding the mechanisms by which a minimalist lifestyle may improve well-being.

6. Minimalism in Architecture: The Ability to Choose Less

In the 20th century, notable architects like Walter Gropius, Philip Johnson, and Le Corbusier consistently pushed the limits of architecture. Minimalism was transforming architecture in a fresh way. The best adage, however, is "Less is More," which was coined by German-American architect Ludwig Mies Van Der Rohe. A philosophy known as "less is more" promotes the placement of only what is necessary in a space and the removal of clutter to allow room for significant items and substance [47]. The goal of minimalist architecture is to construct beautiful structures out of only what is required. The relaxing ambiance that minimalism creates is facilitated by clear lines and shapes, a controlled colour palette, and straightforward materials. The reduction of a subject to its essential elements is referred to as minimalism in design and architecture. The primary objectives of minimalist architects are the connection between two immaculate surfaces, tasteful lighting, and the empty spaces created by the removal of three-dimensional objects [48].

Architects adopted the term "minimalist architectural style" to characterise the aesthetics. The essential components of a building were designed to provide the impression of extreme simplicity by utilising every feature and detail for both aesthetically pleasing and utilitarian purposes [49]. Designer Buckminster Fuller (1895-1983) adopted the engineer's maxim of "Doing more with less," but his concerns were more centred on technology and engineering than on aesthetics. In minimalist architecture, concepts like reduction, simplification, and unity are also demonstrated [7]. Minimalists consider these elements to be the "essence" of building.

Fig. 5 Minimalist architecture (Source: https://www.archidaily.com)

6.1. Minimalist Architects and Notable Work

Kazuyo Sejima, a well-known Japanese minimalist architect, teams up with Ryue Nishizawa as SANAA to produce distinctive Japanese Minimalist structures. Works include House Surrounded by Plum Trees (2003) in Tokyo, and New Museum (2010) in New York City [7]. Another Japanese minimalist architect, Tadao Ando, uses his designs to convey both his own interpretation of nature and the spirit of old Japan. His creative ideas are inspired by geometry, natural materials, and the world around us. He usually combines concrete or natural wood and a minimal structural form to create austerity and rays of light in space. Ando's works and the translation of Japanese aesthetic ideas have had a significant impact on Japanese architecture [49].

Le Corbusier is still a hotly debated topic. His approaches to urban planning have come under fire for disregarding equality, societal expression, and pre-existing cultural sites. The Ronchamp Notre-Dame-du-Haut chapel and the Sainte Marie de La Tourette convent are two of his most well-known creations. Le Corbusier's design for Chandigarh City was one of his largest and most complex projects. Spirit, light, and order are the guiding ideas of British minimalist architect John Pawson's designs. Mies was one of the first designers to apply the adage "less is more" to their work. The architect known as Mies, worked to achieve simplicity and clarity in his designs throughout World War I. He and others used structures, furnishings, and instruction as means to strip architecture of its ornament. Among his famous U.S. projects are the Seagram Building in New York, the Farnsworth House, as well as the Chicago Federal Center complex. His following works were based on these timeless classics. Another renowned architect Laurie Baker born in England in 1917, relocated to India in 1945 and kept on his architectural career there. Baker, a minimalist in style, focused on producing structures that were economical and energy-efficient while using straightforward, locally available materials to produce excellent designs [50].

6.2. Present and Future of Minimalism

The rise of minimalism is a reaction to overconsumption. The "Social movement striving to enhance the rights and power of consumers about sellers" is known as consumerism [51]. Many people who have adopted a minimalist lifestyle in a culture that is frequently associated with extravagant extravagance have done so while still maintaining the core of their respective traditions.

Nowadays, minimalists all around the world are choosing a zero-waste way of living. Whether designers are building homes or businesses, people are consciously choosing to build sustainable constructions. Modern minimalism in architecture frequently uses cosier, more rustic wood. While the minimalist idea is still present, it is clear from the return to natural materials and the addition of stone accents that the design now has a cosier, more recognisable appearance that was lacking in the sterile glossy renditions.

"Doing more and better with less" is the goal of sustainable consumption and production. Its goal is to improve net welfare gains from economic activity by lowering resource use, degrading environmental conditions, and polluting the environment while improving quality of life. The goal is to satisfy consumer demands without going beyond ecological bounds. The need for measures that maximise the value of output and fully utilise resources is demanded, and as a result, dependency on the already overburdened infrastructure and urban areas is anticipated to considerably increase [52].

Although it has flaws, minimalism is not a new idea. In the twenty-first century, minimalism has taken the form of a cornerstone infiltrating the worlds of cuisine, fitness, fashion, architecture, and digital media, and remaking the modern way of life along the lines of traditional and ecological practices. On one hand, a minimalist lifestyle is the most practical way to live [53]. It can, however, be challenging to fully adjust. As a result, minimalism's future is likely to be subjective, believable, and critical.

7. Minimalism and Islamic Architecture

"And do not waste; indeed Allah does not like those who are wasteful …." [55]

The main ultimate realization and substance of nature, as well as natural occurrences that are unified by industry and human invention, must be provided by humans, according to Islamic thinking. Additionally, to impart the perfection that those things possess in relation to their nature to the manifestations and gifts that are available to him [56]. The spaces that have been created by humans must offer a means of drafting the natural environment and the progression toward perfection. Like other arts, architecture serves to enhance productivity in the natural and human environments [57]. To balance what the advantages of the ideal state are [58]. Accordingly, the ultimate aim of architecture was not only the construction of a shelter but also the perfection of the human being and, outside of him, the environment and the natural world that the architecture took place in.

According to Norman El Kons, the goal of sacred architecture is to "clearly define the boundary between the material and the mind, body, and spirit." Regarding religious structures, Priest Robert Shoulder stated that in order for people to be mentally well, they must be in their natural environment, which is a garden. Despite linguistic and cultural differences, sacred Islamic architecture has a uniform identity throughout the world. Naturally, after conversions to Islam, the construction of Islamic places of worship became necessary for religious purposes. The mosques served as the city's primary focal point [59].

The two notions' analysis could be used to interpret minimalism in Islamic philosophy; Zuhud (asceticism, renunciation) and Taammul (contemplation, meditation), which both discovered sufism to find their practice. For the sake of spiritual transcendence, the first notion calls for a separation from the physical world and a minimal lifestyle [60]. It is thought that the physical surroundings, daily routine, and surroundings frequently prevent the mind from attaining greater levels of abstraction. As a component of the physical world, architecture should be given the bare minimum of Muslim thought. Maximizing pleasure, consumerism, and comfort runs counter to this idea [61]. The Prophet's house, his mosque in Medina, and the shape of the Ka'ba [62] may also reflect minimalism in Muslim ideology; this was seen by Creswell to indicate a "desire" for building. For example, it is advised against including any decorations or aesthetics inside the mosque since these elements would interfere with the essence of prayer, that is ‘contemplation and reverence’ which is Khushuu' [63]. Fully ornamented mosques were thought to be a reflection of a degraded faith and a devotion to futility. The nomadic lifestyle in the early Islamic culture appears to have been characterized by simplicity and minimalism. Before most early towns, including Kufa, Basra, and Fustat, the tent served as the bare minimum of shelter [64]. Typically, ornamentation solely refers to features of architecture and building materials. Rooms are versatile areas with little, lightweight furnishings. Prior to the arrival of modernity and industrialization, which brought heavy and fixed furniture; this was the custom in the majority of homes in the Islamic world.

In this context, openness to the sky would also be regarded as a minimalist style that encourages reflection. Every structure, including homes and mosques, has a courtyard in the middle to provide people access to some of the sky. Most frequently, these courtyards served as a landscape feature that brought together various natural components including light, water, vegetation, and soil. Such a typology and spatial layout will undoubtedly encourage reflection more than high-rise structures that provide a horizontal perspective of the street and nearby properties.

The main principles of minimalism include internal and external syndication, using simple geometric shapes, eliminating any luxuries, avoidance of restriction and absolute governance and following the scientific method (Figure 7). The picture makes it obvious that the most crucial guidelines involve simplicity (the elimination of any ostentatious items and non-Islamic components), avoiding constraints, employing basic geometric shapes, according to scientific principles, and connecting the inside and outdoors. The diagram below shows the fundamentals and characteristics of Islamic architecture that have been noticed all over the world, not because of any particular nation or geographic location, but rather because of the religion and mentality of Islamic civilization. The seven mentioned principles of Islamic architecture, as shown in the chart, encompass the characteristics that are thought to be important for Islamic buildings. Islamic schools of minimalism and Islamic architectural elements have been compared in order to determine whether Islamic architecture adheres to its ideas. Islamic architecture completely adheres to minimalist principles and covers them, as seen in the diagram (Figure 7).

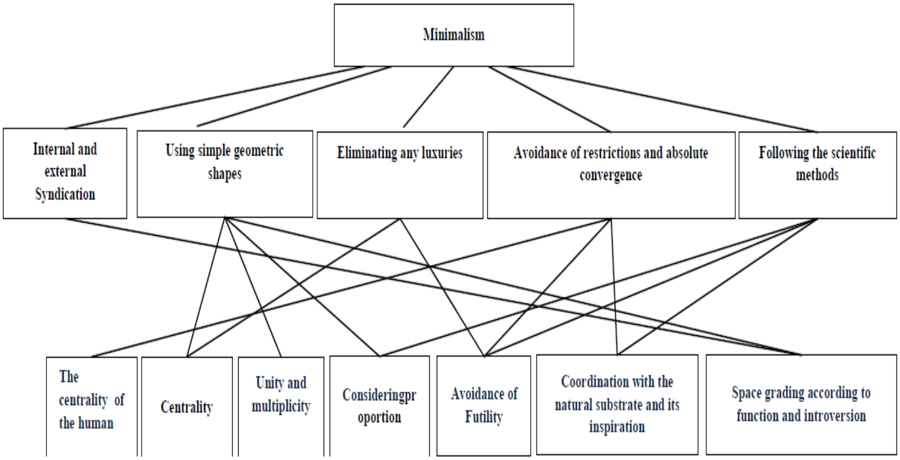

Fig. 7 Characteristics of Islamic architecture with school of minimalism (Source: https://www.bretj.com)

8. Sustainability: a Way to Contemplation

Although it is built on the idea of regionalism, sustainable architecture urges us to use technology wisely and to design for the long term rather than urging us to go back to the ways of the past out of nostalgia [65]. "Sustainable development is the development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [66]. The ecological component, which describes the state of the earth, is the first and most crucial of the three pillars of sustainability [67]. People work to raise awareness that something needs to done to stop global warming and the natural disasters it causes since scientists from all around the world have discovered that humans are responsible for climate change [68]. Additionally, the alteration of ecosystems or biological variety may affect human systems as well [68]. The social and economic aspects of the other dimensions may also be impacted by this. The nested model emphasizes how dependent the economy and society are on the environment and that both are a subset of the environment, in contrast to the three-ring sector perspective of sustainability, which equates to environmental, social, and economic sustainability [67] (Figure 8). The idea of sustainable development and sustainable design is based on following appropriate steps from conception to the production of ecologically sound items. Thusly created products are durable, dependable, adaptable, upgradeable, suited for a variety of uses, and flexible [69].

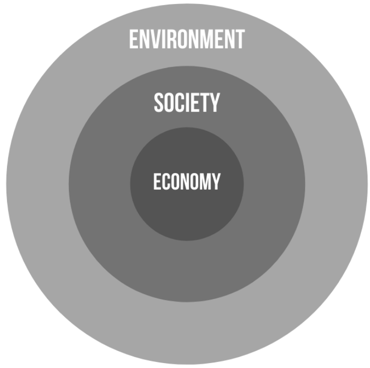

Fig. 8 The nested model of sustainability (Source: https://doi.org/10.1002/sd.199)

In the past, including ecological concepts in planning was a quite pricey procedure. Design choices were made solely based on economic and technological considerations. The effects on the environment of this strategy ran counter to the reasoning of the used design principles. The objective of a novel concept in product development is to decrease significant amounts of waste while preserving non-renewable resources.

8.1. Ecological Labels and Standard

Industrial and production firms have a significant impact on environmental degradation. Numerous industrialised nations have developed national and municipal strategies and begun enacting environmental laws in an effort to reduce the effects of air, soil, and water pollution. Without sacrificing the quality of the finished product, there is a trend to lessen the negative influence on the environment. The use of eco-labels and green insignia helps to market ecologically friendly goods. They carry consumer-facing information that reveals a product's environmental quality.

According to statistics, people in cities spend 80% of their time indoors. As a result, it is crucial that their living and working environments reflect their needs. Green structures are regarded as safe, high-level environmental protection facilities. They are anticipated to be highly comfortable, energy-efficient, and predominately reliant on renewable energy sources. As a result, they have a substantially lower environmental impact than typical buildings [70]. Adopting the idea of sustainable planning and design at a young age is crucial for future generations of engineers, managers, and designers. It is a good practice applicable in many engineering and decision-making areas. Significant financial savings, increased material and energy efficiency, and a healthier environment for the general public will all result from it.

9. Resources Conservation: the 3R's (Reduce, Reuse, and Recycle)

In the past, including ecological concepts in planning was a quite pricey procedure. Design choices were made solely based on economic and technological considerations. The effects on the environment of this strategy ran counter to the reasoning of the used design principles. The objective of a new idea for product development is to protect non-renewable resources and lessen massive amounts of waste (Figure 9). By extending the product's useful life, reusing it (for the same or a different purpose), and recycling a portion or the entire product, the product becomes environmentally benign and ecologically acceptable. Production is concentrated on developing waste-free methods that would enhance output with minimizing the adverse effects on the environment [71]. From the extraction of raw materials to transportation, processing, and production, the environmental impact of resources and products must be monitored. Finally, after use, their remains are handled (disposal, reuse, recycling). The components that are prone to wear, such as floors, should be given special consideration in order to extend the product's useful life.

Fig. 9 Conservation of resources (Source: www.znrfak.ni.ac.rs/SE-Journal/index.html)

The development of alternative materials, the range and accessibility of organic items on the market, and the wide availability of new technology make the ecological design practical and applicable. It ought to be made a prerequisite strategy and a guiding principle in planning and design [72]. The materials used must if at all feasible, be sustainable, environmentally friendly, and safe for human health and the environment. A replacement should be offered for any materials that are unreliable or harmful to use. One of the top considerations in interior design is creating a healthy environment. Only non-toxic, recyclable, and energy-efficient products with low environmental impact should be taken into consideration.

10. Minimalism and Sustainability

Minimalism includes conscious and critical consumption [73] [74] [75] [76]. Given that sustainable consumption can take several forms, it is possible to tie it to this reduction strategy. It either entails using fewer resources, using greener products, or doing both [75]. Most research on minimalism and related consumption habits has focused on individuals and their individual lifestyle preferences. As fewer resources are consumed and depleted, reduced consumption and production are generally more environmentally friendly than excessive consumerism [74] [76] [77].

Researchers have looked into the connection between sustainability and these minimalist living philosophies. They discovered that minimalism traits frequently align with sustainability ideals [73] [74] [75] [76] [77] [78]. People who identify as minimalists frequently also have a keen sense of justice and the environment. Natural science researchers also looked at how minimalism can help people choose sustainable lifestyles and become more aware of sustainability. Their "first hypothesis" is that "reaching sustainability in the long run in all domains of human activity requires knowing, accepting, and enacting simplicity in our daily lives" [78]. They demonstrate that, under scientific circumstances, voluntary simplicity (VS) has a stronger connection to sustainability than minimalism, although they still detect a high correlation between minimalism and environmental behaviour. More effort and investigation are invested in decision-making when there is a decline in consumption and a skeptical attitude toward making new purchases [74]. The potential of minimalism as a way of life and its high standards are pushing manufacturers toward more environmentally friendly production methods. Conversely, research suggests a link between materialism and a lack of interest in environmental issues [76] [77]. The majority of cited research link minimalism to particular characteristics, advantages, or values. Critical consumer analysis and a general understanding of the environment were cited in relation to sustainability, particularly a sense of ethics [75] [78]. In this way, a link between simplicity and sustainability is demonstrated.

10.1. Holistic Approach

The primary characteristics of the design approach are to consider the structure as a whole and to keep things as straightforward and sustainable as feasible. In this way, Sir Patrick Geddes (1854–1922), a Scottish biologist, sociologist, and urban planner, who popularised the phrase "think locally, act globally," served as an inspiration for Liddell. Geddes believed that the health of the world needed to be taken into account as a whole and that individuals needed to take action in their own neighbourhoods and cities in order to attain it. He believed that because society, the economy, and the environment are inextricably linked, any truly sustainable growth must have a positive impact on all three. The notion of the "three-legged economic stool" was developed by Howard Liddell using this idea as the basis. The legs of this stool are the Folk-Place-Work, which are the three pillars of sustainable development. The entire structure will collapse if one leg fails, according to "does not work" [79].

In addition to reducing emissions and energy use, healthier indoor and outdoor environments free of VOCs and other contaminants are also created. The health of the occupants and their productivity is promoted by reducing the toxicity of enclosed spaces [81]. Since it fosters a healthier environment and lowers the cost of medication, this has an impact on both the economy and society of the town. Thermal mass, adequate insulation and airtightness, and natural ventilation reduce the environmental effect while lowering building, operating, and maintenance expenses. A new project or development should therefore have as little of an impact on the environment as feasible.

10.2. How Minimalism Encourages Sustainable Living

The prerequisites for the development are in three phases, as was previously mentioned:

- Keeping the environment safe
- A harm-free economic system and
- Activities that help everyone fulfill their fundamental needs and rights. Living in safe and healthy neighbourhoods. Thus, non-discrimination and equality for all.

One of the pillars of sustainable environmental development is to minimize the number of consumed items and attempt to limit the consumption of natural resources since minimalism is the practice of living a minimal life, which is a way of decreasing the consumption of luxury goods and waste. Here, we can see how sustainable development and financial performance are related. Every person should be able to see themselves and their family in the face, which is one of the objectives of the sustainable economic pillar. Here, the minimalist aims to put more emphasis on the important things than on the money. Money is spent on things that are required and important, so this strategy eliminates waste. The minimalist approach, on the other hand, emphasizes morals and human values in society and is a link to sustainable development, which aims to create healthy and secure societies. The connection between sustainable development and the minimalist approach is a sensible method for putting one of the concepts of sustainable development into practice, and if we use it, it will also result in a significant shift [82].

11. Low Consumption Style: Well-Being and Economical Influence

People who lead low-consumption lifestyles and engage in pro-environmental, thrifty, and voluntary simplicity tend to refrain from excessive consumption and the acquisition of material goods. The health of the building's occupants is another crucial factor that may be inferred from the eco-minimalist approach, in addition to minimizing the environmental impact and financial expenditures. Less than 3% of the materials used in buildings have undergone testing for their ability to cause cancer or have any other negative effects on the human body. While VOCs like formaldehyde can worsen asthma, especially in children, and induce headaches, nausea, and dizziness, air pollution can also cause allergies and a generally unpleasant environment [83]. To prevent decomposition, otherwise healthy and natural materials are frequently chemically treated with hazardous preservers, which transform them into poisonous materials that can harm human health and are impossible to dispose of without contaminating.

Lighting is another element that affects a user's well-being. An "important contribution to peoples' experiences of buildings" is "daylight" [81]. In order to produce a high-quality area, any conditions that cause glare or overheating should be removed during the design process [82]. Studies frequently suggest a connection between intentional simplicity and increased well-being, although there are not much concrete data to back this up [85] [86]. The relationship between thrift and well-being has also been described as "a lifestyle of strategic under-consumption." It should be mentioned that not everyone can lead a simple lifestyle in the way that is presented. Because they do not have the means to afford many items, those who are not financially stable cannot have the issue of overconsumption [73]. Minimalism has economic benefits as well because it encourages the thoughtful consumption of only the things one needs [87] [88]. Because of the opportunity to save and pursue long-term goals, the financial stability contributes to greater well-being [89].

12. The SWOT Analysis

The SWOT analysis is a strategic planning and strategic management technique used to help a system or organization identify Strengths, Weaknesses, Opportunities, and Threats related to decision-making and project planning. It is sometimes called situational assessment or situational analysis. This technique is designed for use in the preliminary stages of decision-making processes and can be used as a tool for the evaluation of the strategic position of organizations of many kinds. The users of a SWOT analysis often ask and answer questions to generate meaningful information for each category to make the tool useful and identify their competitive advantage. Following is the SWOT analysis for the application of Minimalism in Architecture has been summarized in Table 1.

Table 1 SWOT Analysis for the application of Minimalism in Architecture

Strength	Weakness	Opportunity	Threat
Many well-being advantages, according to minimalists, include happiness, life satisfaction, meaning, and strengthening interpersonal ties.	The biggest problem with the minimalist movement is that there is not much information out there. As a result, information is spread and the overall idea is frequently misunderstood.	People today favour sustainable choices that take into account various environmental issues. More people are upcycling and thrifting, which opens up more chances for business aficionados.	The practice of minimalism is not without possible drawbacks. Minimalism is frequently dismissed as just aesthetic, a luxury only available to those with more financial means.
One may be able to develop a more effective strategy to manage their feelings and health if they can learn to reduce stress by cleaning their environment.	In the past, people have abused minimalism by raising the prices at which they sell worn goods. Such instances erode the movement's strength and lead people away from minimalism.	All nearby internet retailers have switched to eco-friendly packaging.	A minimalist lifestyle, according to some critics, promotes and facilitates new types of consumption, and minimalism is only a "cure-all for a certain feeling of capitalist overindulgence" [54].
Consumption at a high rate results in more waste. Because of this, many minimalists adopt "zero waste" practises, which go beyond simply lowering consumption [54].	Because they perceive minimalism as being overused, people are reluctant to give it a try. Even more people experience shame.	Through books, blogs, articles, and videos, individuals today are attempting to learn more about living a minimal lifestyle. As a result, there is a rise in the demand for writers who promote sustainability.	These new consumption patterns may take the shape of a desire to buy products that serve are sustainable or conserve energy, or one may modify home to conform to the minimal space requirements [54].
Another advantage of living a simple life is that one leaves less of a carbon impact.	The benefits of minimalism and what it truly is are not well known by the general public.	Writing with a minimal vocabulary aims to convey as much information as feasible while using the fewest number of words possible. It is the marriage of simplicity and clarity [18].	Some people find decluttering to be onerous because they become fixated on what to get rid of and how many things they "should" own.

13. Discussions

In order to gain a clearer knowledge of the advantages of minimalism for wellness, the aim of this study was to investigate what it is like to live a minimalist lifestyle.

13.1. Social and Sustainable Paradigm Change

It is widely acknowledged that our planet urgently needs to adopt more sustainable purchasing habits. Sustainability in a comprehensive sense has only recently attracted the attention of social academics, having previously been relegated to primarily being an environmental issue [90]. Sustainability cannot be attained simply by avoiding unsustainability; rather, a cultural paradigm shift is necessary, as is explored in the book "Flourishing." While fair trade and eco-efficient production are not inherently wrong, they do not represent true sustainability as flourishing. Long-term prosperity can only result from the formation of a society that rejects materialism and slows the market. According to research, adopting true honesty is crucial to making the transition from a culture of possession to one of spirituality and transcendence. The idea of caring must take the place of the Cartesian model's dominance in economics. They contend that despite economists' continued predictions of a future characterized by a hedonistic consumerism, "homo ludens" nevertheless yearns to escape the inhumane confines of the consumerist treadmill of synthetically produced desires. Hoskins states her belief that the current capitalist model cannot be changed in 2014. She makes the point that, rather than changing the approach, the purpose must change in order to improve the condition of the planet.

13.2. Designing a Sustainable Future

The use of daylight, separate operating zones for artificial lighting, and control by daylight sensors, natural forces like air pressure and wind for ventilation, control of airflow, heat recovery, and low-emitting building materials, geothermal heat, and alternative building materials, such as transparencies, are some of the energy efficiency and conservation strategies. There appears to be widespread agreement in modern architectural discourse and practice regarding the urgent need to support environmental innovation in building design. We are discovering that a straightforward, compact building shape is essential for achieving extremely low energy use. Things should be as simple as possible, but not simpler, according to Einstein. The obvious solution is a simple box, and architects like Peter Zumthor have shown that even the simplest of boxes can look sophisticated and elegant [91].

14. Conclusions

Design minimalism's potential is continually being explored. People may find the minimalist trend fascinating, but it also carries a heavy burden of responsibility. The following aspects are related to aesthetic attributes that help products be more sustainable: features that last a long time, aesthetic aging (flexibility), timeless design (anti-fashion), market policy (slow changes of aesthetic values in the market), long life, and style. Choosing to live a minimalist lifestyle involves letting up material belongings that do not enrich our lives. Sustainable designs should overtake conventional ones that are not sustainable. Making anything may seem easy and straightforward, but when a designer has had a glass of minimalism, they will realize the nuances of making items with little assets. This is a serious issue for architects as well. The aesthetic values of nature that are ingrained in cultures and traditions are highlighted by aesthetic sustainability. The incorporation of traditional aspects is encouraged by designers. The foundation of a sustainable design approach is a method of revisiting and improving archetypes. Although there are numerous benefits to minimalism, there are some negatives as well. Designers cannot hide errors, and many people find the absence of adornment and the neutral colour scheme unappealing.

Islamic architecture differs from other styles in a variety of ways, although having many traits in common with minimal-style basic structures. Islamization of architecture is based on principles that apply to many other fields of study and come from the core of Islamic philosophy. The abundance of human knowledge that contemporary architecture(s) offer should also be subjected to Islamization, a crucial process of filtering and re-theorizing that depends on these systems. Many movements, like participatory and environmental trends, for example, might be fully adopted, while others, like deconstruction and minimalism, could be redesigned in accordance with Islamic norms. Through the concepts of symbolic loading and image creation, the minimalist aesthetic can influence the socio-cultural and economic aspects of sustainability. The aesthetic values of nature that are ingrained in cultures and traditions are highlighted by aesthetic sustainability. The incorporation of traditional aspects is encouraged by designers. A technique for revisiting and upgrading archetypes forms the basis of a sustainable design strategy. Eco-attributes must not result in decreased product performance or rising unit costs. In order to compete in marketplaces where the survival of the economic fittest is the norm, sustainable products must maintain the level of fundamental characteristics and cost structure that make them competitive.

Many people would opt for Mies van der Rohe's succinct adage, "less is more," if we had to sum up minimalism in a sentence or two. At the time, minimalism permeates both our daily lives and architecture. Perhaps for this reason, minimalism has come to stand for something.

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MINIMALIZAM U ARHITEKTURI: OSNOVA ZA OČUVANJE RESURSA I ODRŽIVI RAZVOJ

Na nov način, moderna arhitektura ima veliki uticaj na današnju savremenu arhitekturu. Od kasnih 1980-ih, „minimalizam u arhitekturi se uzima u obzir. Naglašeno je manje je više, što se pridržava filozofije ispunjavanja prostora potrebnim stvarima i uklanjanja nepotrebnog nereda kako bi se ostavio prostor za značajne materijale i predmete. Sa jednostavnim oblicima i jasnim linijama, neutralnom *shemom boja i jednostavnim teksturama, minimalizam odiše smirenošću. Minimalizam znači odbacivanje preteranog u životu. Možemo pronaći slobodu, zadovoljstvo i sposobnost da se koncentrišemo na ono što je najvažnije. Bez obzira na to da li se dogodio u eri održivosti ili u dvadeset prvom veku, minimalizam usvaja konvencionalni način života „manje je više“. Osim što prikazuje širok spektar nijansi, arhitektura je oblik umetnosti. Iranska arhitektura utelovljuje istorijsku veličinu i predanost, posvećenost verskom obrazovanju i odbacivanje materijalizma. To je proizvod islamske civilizacije. Međutim, recikliranje dobro poznatih arhitektonskih obeležja poput minareta, dvorišta i mašrabije često se kosi sa modernim trendovima u arhitekturi, koji nisu nužno suprotni osnovama islamske arhitekture. Minimalizam se smatra osnovnim resursom i alternativom sadašnjoj standardnoj estetici. Kako bi skrenuli pažnju projektanata sa održivim ciljevima na odnose između minimalizma i održivosti, sledeća pitanja su ukratko obrađena u ovom radu: Kako funkcioniše minimalistički dizajn? Šta podrazumeva minimalistički dizajn? Da li je minimalistički stil najbolji stil za ekološki prihvatljivu arhitekturu? Ovaj rad pokušava da ispita minimalističku estetiku održive gradnje i dizajn. Ovaj rad razmatra sveobuhvatan pregled i analizu minimalizma i njegovih vodećih principa u arhitekturi. Također se nastavlja iscrtavanjem karakteristika i minimalističkih osnova islamske arhitekture.*

Ključne reči: *Minimalizam, Minimalistička Arhitektura, Jednostavnost, Održivi Razvoj, Ekološka Održivost, Očuvanje resursa*

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DESIGN OF NAILED TIMBER-CONCRETE COMPOSITE JOINT ACCORDING TO EUROCODE AND FEA

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624.016.04

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Abstract. *During rehabilitation of residential buildings built in the first half of the 20th century, it is necessary to strengthen timber floors so they can fulfill the requirements of strength and serviceability according to contemporary regulations. Floors made of monolithic timber girders can be most easily strengthened by forming a composite structure with a reinforced concrete slab supported on a trapezoidal steel sheeting, with appropriate connections between different materials. In the paper, the procedure of calculation of nails used as shear connectors for composite action of timber and concrete is presented. The procedure is based on equations given in Eurocode 5, and besides that, a calculation applying FEM has been conducted, and a comparison of results is presented.*

Key words: *composite action timber-concrete, nail, rope effect, Eurocode 5, FEM*

1. INTRODUCTION

Composite floors consisted of timber girders and reinforced concrete slab lied on a trapezoidal steel sheeting have broad application in construction. They can be used as for sanation of old timber floors, as well as at newly designed girders. Buildings erected in the first half of the 20th century mostly have floors made of timber girders, and because of their poor state a need for some structural intervention arises. In most cases, the existing structure cannot be kept without some kind of strengthening (Maslak, et al., 2020), because of their unfavorable characteristics regarding vibrations (Kozarić, 2016).

One of the methods of improvement of the characteristics of a timber floor is by composite action with added reinforced concrete slab. As a form, a galvanized steel trapezoidal sheeting TR60/210 with thickness of 0.5-0.6 mm is used in most cases. This

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technique increases the mass of the floor structure, which is unfavorable. However, this significantly increases the structural stiffness. Comparing the drawbacks and the benefits of this technique, one may conclude that the final effect is favorable (Milić, et al., 2021). Achieving of the adequate stiffness of the girder could not be possible without appropriate shear connectors, which connect the new reinforced concrete slab with the existing timber girders.

Shear connectors for composite action of timber and concrete can have different forms: nails, bolts, steel bars, steel tubes, carpentry joints, etc. Combinations of different types of dowels can be also used (Stevanović, 2004; Khorsandnia, et al., 2012; Hassanieh, et al., 2016; Stojić and Cvetković, 2001). Contemporary construction practice requires simple and fast installing of shear connectors, with satisfying characteristics regarding their strength and serviceability. Bolts and nails are the most often used types.

In this paper, the strength of the joint of a timber girder and a reinforced concrete slab supported on trapezoidal steel sheeting performed by nails is analytically defined. For the purpose of strength calculation of the joint, the equations according to the Johansen's procedure (Johansen, 1949), adopted in Eurocode (EN 1995-1-1, 2004), are used. Besides that, the joint has been modelled and calculated applying the Finite Element Method (FEM), and the obtained results have been compared with the results of the analytical calculation.

2. SETTING OF THE PROBLEM

In this research, the task was to strengthen timber floor structure presented in **Error! Reference source not found.**. Timber girders with cross section 180/200 mm were set at mutual distance of 800 mm. Timber grade was adopted as C24 (EN 338, 2009). The rehabilitation was performed by concreting the slab over the steel trapezoidal sheeting TR 60/210, that was previously set over the timber girders. The ribs of the trapezoidal sheeting were set perpendicularly to the timber girder direction. After concreting, the thickness of the concrete slab was 110 mm over the troughs, and 50 mm over the ridges of the sheeting. The concrete class was C30/37 (EN 1992-1-1, 2004), and the slab was reinforced by wire-mesh reinforcement Q84.

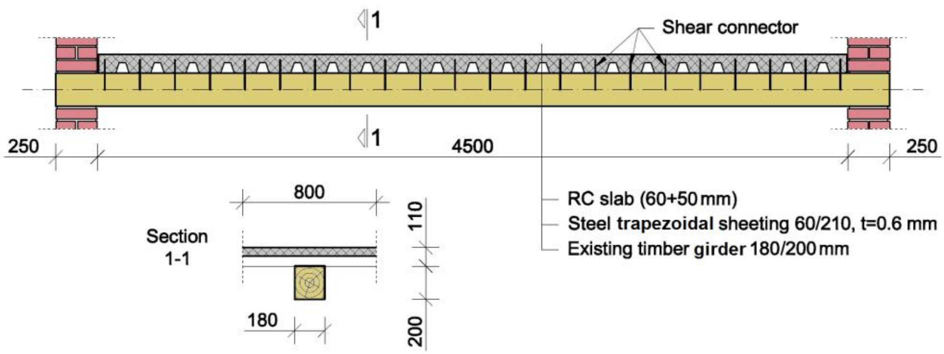

Fig. 1 Disposition of the rehabilitated floor (Milić, et al., 2021)

For joining the timber girder with the reinforced concrete slab, nails E70/200 (Ø7 mm, total length 200 mm) were used. The nails are fabricated of wire with ultimate strength $f_u = 600$ MPa (EN 1995-1-1, 2004). Half of the nail length is embedded in timber, and half in concrete (**Error! Reference source not found.**).

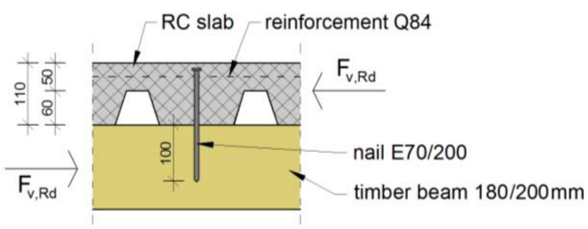

Fig. 2 Detail of the analyzed joint

3. Modes of Failure and Calculation by EUROCODE 5

The Eurocode 5 standard does not provide an exact procedure for determining the strength of the joint of a timber girder and reinforced concrete slab supported on trapezoidal sheeting performed by nails. However, the equations defined for other joints given in Eurocode may be used, like the joint between a thick steel element and a timber element. In such case, the nail is considered as fixed into the steel element. Applying analogy, this case is used for the research in this paper, whereat instead the steel element, a RC slab is introduced. The stiffness ratio between an RC slab and a timber element is lower than the ratio between steel and timber, but still sufficiently high to justify the analogy used.

Considering the previous, one may say that the RC slab in this joint is absolutely stiff, and therefore it is not a subject of calculation. Taking into account the mentioned analogy and the failure modes for this type of joint given by Eurocode, the following types of failure modes are proposed (**Error! Reference source not found.**).

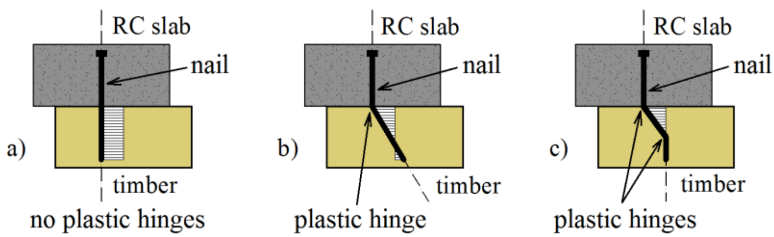

Fig. 3 Possible failure modes of the analyzed joint

The first failure mode of the joint (**Error! Reference source not found.**a) implies that an exceedance of the embedment stress in timber occurs, without forming a plastic hinge in the nail. Such failure mode is unfavorable, because the failure occurs abruptly (brittle failure). In the second failure mode, a plastic hinge occurs in the nail at the slipping plane, and the part of the nail in the timber volume acts as a rigid body (**Error! Reference source not found.**b). In the third failure mode, two plastic hinges arise. Exceedance of the embedment stress in timber occurs here too, but only in the part of the nail between the two plastic hinges (**Error!**

Reference source not found.c). The second and the third mode represent ductile failure modes, due to the plastic hinges developed.

In the failure modes where plastic hinges arise, an elongation of the nail occurs, which generates an axial force in the nail, causing the so-called rope effect. This axial force compresses the timber girder and the RC slab against each other, and activates friction between the two materials. This phenomenon decreases the slip in the joint, thus increasing the total strength of the joint. In the Eurocode standard (EN 1995-1-1, 2004) it was adopted that contribution to the joint strength due to the rope effect can be taken as one fourth of the withdrawal capacity of the nail, but not greater than 15 % of the primary part of the capacity, denoted as Johansen's part. According to this, the final expressions for the analyzed joint strength are:

$$F_{v,Rk} = \min \begin{cases} f_{h,k} \cdot d \cdot t_{pen} \\ f_{h,k} \cdot d \cdot t_{pen} \left[\sqrt{2 + \dfrac{4 \cdot M_{y,Rk}}{f_{h,k} \cdot d \cdot t_{pen}^{\,2}}} - 1 \right] + \dfrac{F_{ax,Rk}}{4} \\ 2.3\sqrt{M_{y,Rk} \cdot f_{h,k} \cdot d} + \dfrac{F_{ax,Rk}}{4} \end{cases} \quad (1)$$

where: $f_{h,k}$ – characteristic embedment strength of the timber,
d – nail diameter,
t_{pen} – penetration length,
$M_{y,Rk}$ – characteristic nail yield moment,
$F_{ax,Rk}$ – characteristic withdrawal capacity of the nail.

Characteristic embedment strength of the timber may be determined experimentally (EN 383, 2007), or using the formula for nails built-in into previously drilled holes:

$$f_{h,k} = 0.082 \cdot (1 - 0.01 \cdot d) \cdot \rho_k \quad (2)$$

where ρ_k is the characteristic value of the timber mass density in kg/m^3. Characteristic nail yield moment is determined based on the nail diameter and steel grade, according to the research (Blass, et al., 2001):

$$M_{y,Rk} = 0.3 \cdot f_u \cdot d^{2.6} \quad (3)$$

where f_u is the ultimate strength in MPa of the steel used for nail fabrication. Characteristic withdrawal capacity of the nail can be determined using the formula:

$$F_{ax,Rk} = f_{ax,k} \cdot d \cdot t_{pen} \quad (4)$$

where $f_{ax,k}$ is the characteristic withdrawal strength, determined by the formula:

$$f_{ax,k} = 20 \cdot 10^{-6} \cdot \rho_k^{\,2} \quad (5)$$

According to the expressions (1), the strength of this type of joint is defined as a sum of the primary (Johansen's) strength and the secondary (rope effect) strength. The strength has to be calculated for every of the three failure modes, whereat the minimal value will be governing.

However, forming of the plastic hinges occurs at the beginning of the loading process, at small deformations in timber and in the nail. The rope effect arises much later, at much greater displacements in the joint, meaning that the failure mode of the joint depends only on the Johansen's strength, and in that phase the rope effect has no influence. Because of that, it is proposed to calculate the values of the Johansen's strength for every failure modes first, and than to determine the governing one. Finally, the rope effect strength should be included, if it exists for the governing failure mode.

For the calculation of the ultimate limit states and serviceability limit states of the composite structures, the stiffness of the joint is essential for determination of the static influences. According to the Eurocode, the stiffness is independent from the failure mode, and it is calculated by the formula:

$$K_{ser} = 2\rho_k^{1.5} d / 23 = 0.087 \rho_k^{1.5} d \tag{6}$$

Using the formulas (1)-(6), the strength of a joint between a timber girder and an RC slab on trapezoidal steel sheeting is calculated for the analyzed case. For the adopted timber class C24, mass density was taken as ρ_k = 350 kg/m^3 (EN 338, 2009). Characteristic embedment strength of the timber, the nail yield moment, and the Johansen's joint strength are presented in Table 1.

Table 1 Characteristic values of the Johansen's part of strength for the analyzed joint

Item	Symbol	Unit	Value
Timber embedment strength	$f_{h,k}$	N/mm^2	26.7
Nail yield moment	$M_{y,Rk}$	Nmm	28350
Johansen's joint strength (mode 1)	$F_{v,Rk,1}$	N	18690
Johansen's joint strength (mode 2)	$F_{v,Rk,2}$	N	8140
Johansen's joint strength (mode 3)	$F_{v,Rk,3}$	N	5290

The lowest value of the Johansen's part of strength was obtained for the third failure mode (**Error! Reference source not found.**c), meaning that this is the governing mode. For this failure mode, the rope effect exists, so the secondary part of the joint strength was calculated (Table 2). At the end of the table, the calculated total strength and the slip modulus are presented.

Table 2 Characteristic values of the rope effect strength, total strength, and slip modulus of the analyzed joint

Item	Symbol	Unit	Value
Withdrawal strength	$f_{ax,k}$	N/mm^2	2.45
Nail withdrawal capacity	$F_{ax,Rk}$	N	1720
Rope effect strength 1 (0.25 $F_{ax.Rk}$)	$F_{re,Rk,1}$	N	430
Rope effect strength 2 (0.15 $F_{v,Rk,3}$)	$F_{re,Rk,2}$	N	790
Strength of the joint ($F_{v,Rk,3}$+ $F_{re,Rk,1)}$	$F_{v,Rk}$	N	5720
Slip modulus	K_{ser}	N/mm	3990

4. FE ANALYSIS OF THE JOINT AND COMPARISON OF RESULTS WITH THE ANALYTICAL EXPRESSIONS

Beside the analytical calculation, strength, stiffness, and failure mode of the analyzed joint have been determined, based on the numerical model, using FEM and software FEMAP with NX Nastran (NX Nastran User Guide, 2016). The model has been built applying line (1D) finite elements. The nail has been modelled using BEAM type elements. The size of the nail finite elements is 5 mm, and there are 20 elements (FE1-FE20), which have been set between successive nodes N1-N21 (Fig. 4).

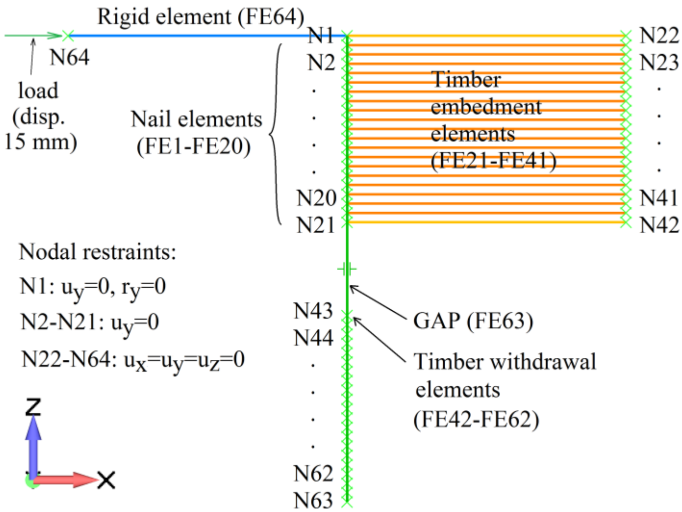

Fig. 4 Setting of the nodes and finite elements in the FEM model (N-node, FE-finite element, u-displacement, r-rotation)

Influence of the timber to the nail has been modelled with elements of ROD type. Behaviour of timber under embedment has been modelled with “timber embedment” elements (FE21-FE41), and behaviour of timber under withdrawal has been modelled with “timber withdrawal” elements (FE42-FE62). All elements lie in plane XZ. For “timber embedment” and “timber withdrawal” elements the length of 150 mm has been adopted. The cross-section area of these elements has been determined based on the embedment area of the nail FE, and it was 35 mm^2.

The material models for the steel of the nail have been adopted as elastoplastic (Fig. 5a). Material characteristics have been determined based on recommendations from literature (Hassanieh, et al., 2016; Nakashima, et al., 2013) and presented by a diagram (Fig. 5b).

Influence of the contact between the steel sheet and the timber has been modelled by GAP element (FE63). This element possesses high stiffness under compression and shear (C=10^9 N/mm), and does not possess tensile stiffness. The adopted friction coefficient was μ = 0.25. This GAP element connects the nodes N1 and N63 (Fig. 4).

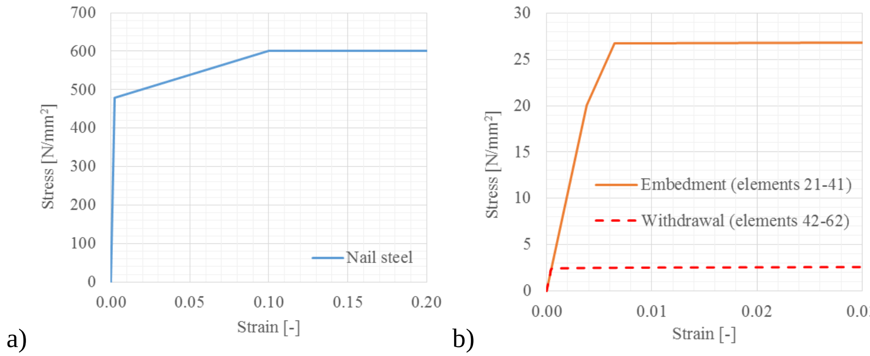

Fig. 5 Stress-strain curves: a) nail steel, b) timber elements

The load is applied at the node N64, in the direction +X, as a displacement of 15 mm (EN 26891, 1991). This load acts on the nail via the ROD-type "rigid" element FE64. Introduction of the rigid element enables easy tracking of the force generated in the joint. Fig. 6 presents the load and the restrained nodes.

The proposed load acts in the X-direction, and the structure can deform only in XZ plane. Because of that, all nodes were restrained in Y-direction. Rotation of the cross-section of the nail at the slipping plane (node N1) is restrained around the Y-axis due to the stiffness of the RC slab, and the nodes N22-N64 are pinned supported.

An incremental nonlinear analysis with 200 steps has been conducted. Nonlinearity encompassed both the material and geometrical aspect of the structure. In this research, the joint strength has been analyzed in three ways:

1. Calculation of the total strength of the joint taking into account the primary (Johansen's) and secondary (rope effect) part of the strength;
2. Calculation of the total strength, as in variant 1, but with friction coefficient in the slipping plane taken as equal to zero;
3. Calculation of the total strength, as in variant 2, but with withdrawal strength of the nail taken as equal to zero.

According to the approaches described above, the following alterations have been made in the initial FE model. In the second variant (var. 2) the friction in the GAP element has been excluded ($\mu = 0$). The third variant of the model (var. 3) has been obtained by removing of the withdrawal elements (FE42-FE62) and the GAP element (FE63). Thus, the nail in the third variant does not possess withdrawal strength, and the rope effect is not present.

Fig. 6 present load-slip dependences for three different analyzed variants. The applied load corresponds to the axial force in the rigid element FE64, and the slip in the joint is equal to the displacement of the node N64 in X-direction. Within the same diagram, the contact force between the steel sheet and the timber, expressed as axial force in the GAP element, has been given for the first and the second variant of the joint, that is, for the variants in which the GAP element exists. The force in the GAP element is equal in both variant, as expected.

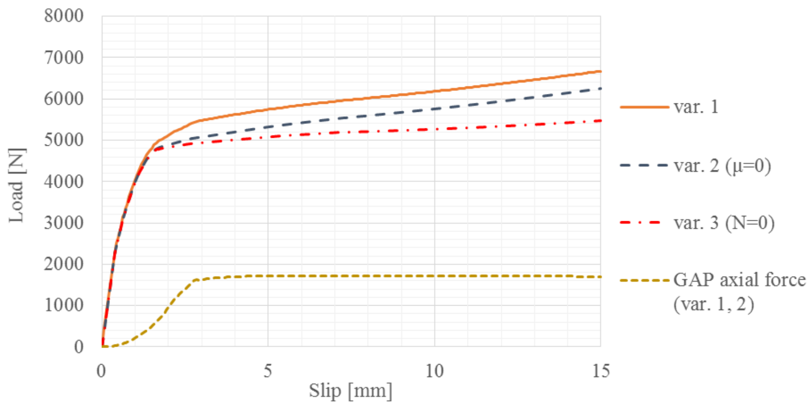

Fig. 6 Results. Load-slip curves for different variants of the joint and axial force in the GAP element for variants 1 and 2 (common curve)

In the Fig. 7 are given contour presentations of the bending moment for the variant 1 and variant 3. One may notice that plastic deformation occurred in the nail cross-sections with maximal bending moment. In this case two plasticized cross-sections occurred, one in the slipping plane, and the other in the timber volume at the depth approximately 30 mm below the slipping plane. The results shown in the Fig. 7 confirm that the failure modes obtained by Finite element analysis correspond to analytical calculation (Section 3, Table 1). Distribution and values of the bending moment in the variant 2 is identical with the variant 1, so they are not presented.

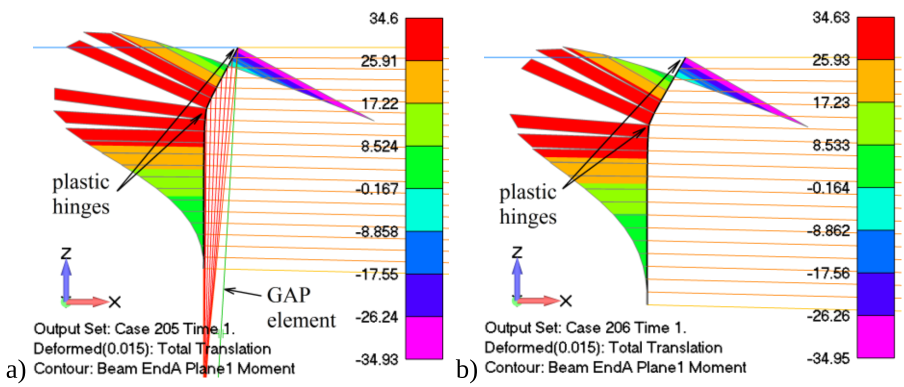

Fig. 7 Results. Deformed model and diagram of the bending moment in the nail: a) model variant 1, b) model variant 3

Table 3 presents comparative results of the numerical analysis and analytical calculation of the joint strength. In the FE analysis, the result value is the total strength of the joint, and one cannot obtain separate values for the primary (Johansen's) and secondary (rope effect) strength. Because of that, the Johansen's strength of the joint strength is identical with the total strength of the variant 3. The rope effect strength at variants 1 and 2 has been calculated as the difference between the total strength and the Johansen's strength. Based on the load-slip dependence at 10 % and 40% of strength, the slip moduli have been calculated (EN 26891, 1991).

Table 3 Comparison of results between analytical expressions and numerical analysis

Item	Symbol	Unit	Analytical	var. 1	var. 2	var. 3
Primary (Johansen's) joint strength	$F_{v,Rk,3}$	N	5290	5480	5480	5480
Withdrawal force	$F_{ax,Rk}$	N	1720	1700	1700	-
Secondary (rope effect) strength	$F_{re,Rk,1}$	N	430	1190	770	-
Total joint strength	$F_{v,Rk}$	N	5720	6670	6250	5480
Slip modulus	K_{ser}	N/mm	3990	5230	5410	5940

From the diagram in Fig. 7 and from Table 3 one may notice that the rope effect exists even in the variant 2, although there is no friction between elements in the slipping plane. This is the consequence of the inclination of the part of the nail between the plastic hinges (Fig. 7). The axial force in the nail is then decomposed in two components, and the component in the direction of load acting increases the joint strength.

The difference of the Johansen's strength between the analytical and the numerical calculation are 3.5 %, confirming a very good agreement between the two methods. The rope effect strength show higher difference. For the variant 1, the FEM strength is 276% of the analytical one, and for the variant 2 the it is 179%.

5. CONCLUSION

The Eurocode standard does not define the procedure for calculation of the timber-concrete joint, so the procedure given for the timber-steel joints is used. In this paper three possible failure modes of the joint were analyzed. For the parameters considered, joint strength was the lowest in the third failure mode, where two plastic hinges occurred. Generally, steel exhibits ductile behaviour. Taking this into account, the failure modes of the analyzed joint that include occurrence of plastic hinges are considered favourable.

The Eurocode proposes one-stage joint calculation, using expressions that include the primary (Johansen's) strength and the secondary (rope effect) strength. According to this methodology, the governing failure mode is obtained as minimum of the summations of the primary and the secondary strength. The drawback of this procedure is that the rope effect is included into the determination of the governing failure mode. However, in reality, the governing failure mode is generated in early stage of the joint slipping, when rope effect has not been developed yet.

In this paper, a different methodology was proposed, that is, to calculate the primary strength first, for all failure modes. Based on these values, one should determine the governing failure mode, taking the minimal value. After that, the influence of the rope effect has to be added, in order to obtain the total strength of the joint.

In the paper, a complex numerical FEM model for the calculation of the considered joint has been developed. The model includes geometrical and material nonlinearity regarding the timber and the steel material. The status nonlinearity has been also included regarding the contact between the sheet metal and the timber at the slipping plane. This phenomenon has been treated applying the contact analysis with use of GAP finite element.

The results of the FE analysis and the proposed analytical calculation of the joint have been compared. The failure mode with two plastic hinges in the nail has been obtained applying both methods, thus showing good agreement.

The comparison of strength values between the analytical and the numerical method showed significant differences. The reason for this lies in the approach taken in the FEA. Namely, since the FEA gives total strength of the joint as a result, three separate analyses had to be concluded. Thereat, the nail element has been treated differently regarding the presence of possible effects:

- embedment strength, withdrawal strength, and friction;
- embedment strength and withdrawal strength;
- embedment strength only.

Based on this, the primary (Johansen's) strength and the secondary (rope effect strength) have been determined. The calculation according to the proposed analytical method and according to the numerical model produce results that are very close regarding the Johansen's strength only. Higher differences derive from the contribution of the rope effect strength, where the numerical model produces significantly higher strength values. These differences show a high reserve of the analytical method (both the existing and the proposed one) considering the calculation of the rope effect.

The proposed numerical method enables a more accurate analysis of this type of joint, with a remark that the embedment and the withdrawal behaviour of timber must be known.

Further improvement of this methodology would include implementing of test results of nail bending, timber embedment, and timber withdrawal behaviour into the FE model.

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PRORAČUN VEZE DRVO-BETON IZVEDENE EKSEROM PREMA EVROKODU I PRIMENOM MKE

Prilikom sanacije stambenih objekata građenih u toku prve polovine prošlog veka, potrebno je ojačati drvene međuspratne konstrukcije kako bi ispunile zahteve nosivosti i upotrebljivosti prema savremenim propisima. Međuspratne konstrukcije od monolitnih drvenih nosača se najjednostavnije ojačavaju sprezanjem sa armirano-betonskom pločom koja se izrađuje na trapeznom čeličnom limu, a spajanje se vrši odgovarajućim spojnim sredstvima. U radu je prikazan postupak proračuna eksera koji se koristi kao moždanik za sprezanje drveta i betona. Postupak je zasnovan na jednačinama datim u Evrokodu 5, a pored toga je sproveden i proračun primenom MKE i dato je poređenje rezultata.

Ključne reči: *sprezanje drvo-beton, ekser, efekat užeta, Evrokod 5, MKE*

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