ISSN: 0974-5823 Vol. 7 No. 6 June, 2022

International Journal of Mechanical Engineering

Aseismic Stiffening of Architectural Buildings as Preventive Restoration Using Unconventional Materials

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***Abstract* -** In the proposed design concept, laminated glass and laminated plexiglass, as "unconventional materials", are considered as a filling in a steel frame on which they overlap by the intermediate rubber layer, thereby forming a composite assembly. In this way vertical elements of stiffening are formed, capable for reception of seismic force and integrated into the structural system of the building. The applicability of such a system was verified by experiments in laboratory conditions where the experimental models based on laminated glass and laminated plexiglass had been exposed to the cyclic loads that simulate the seismic force. In this way the load capacity of composite assemblies was tested for the effects of dynamic load that was parallel to assembly plane. Thus, the stress intensity to which composite systems might be exposed was determined as well as the range of the structure stiffening referring to the expressed deformation along with the advantages of a particular type of filling compared to the other one. Using specialized software whose operation is based on the finite element method, a computer model of the structure was created and processed in the case study; the same computer model was used for analysing the problem in the first phase of the design process. The stiffening system based on composite assemblies tested in laboratories is implemented in the computer model. The results of the modal analysis and seismic calculation from the computer model with stiffeners applied showed an efficacy of such a solution, thus rounding the design procedures for aseismic stiffening by using unconventional materials.

Keywords : *Laminated glass, laminated plexiglass, aseismic stiffening, experiment, laboratory testing, computer model, finite element method.*

INTRODUCTION

In building construction, glass is most often used to partition spaces, as a facade curtain wall or interior transparent partition. This is considered a "conventional way" of using glass. But some authors give a very through account of the behaviour of architectural glass in extreme conditions, such as earthquakes and strong winds [1]. There is also a fundamental literature that provides a general overview of various aspects of the use of glass in construction [2]. When it comes to the behaviour of glass panels, most often within the curtain wall, in seismic conditions, there is a "classic" work [3] in which the mechanism of behaviour is clearly observed, both in the plane of the panel and perpendicular to the plane.

As an integral element of the glass façade, the panels are exposed to significant shear stress during the interfloor movement, with the way of connecting to the substructure playing a very important role. We should also mention [4], where we can find the analyse of stability of the panel with point bonding in the corners, which is a topic that is very close to this paper. In the latest literature, [5] stands out, in which, in order to assess the damage to the curtain wall under seismic loading, extensive experimental and numerical research is presented.

In recent years, there has been interest in involving architectural glass in certain cases in the stabilization of the structure to horizontal, primarily seismic influences [6]. There is work [7] which presents the results of dynamic experimental investigations of wooden frames with glass filling. It is one of the few works in which testing under dynamic load was conducted.

It has been noticed that the main source of energy dissipation is sliding between the glass panels and the wooden frame, as well as in the nodes of the wooden frame itself. There is [8] in which glass panels are used to stabilize wooden frames. The connections between the panels and the frame are based on epoxy, silicone or polyurethane. Experimental tests were performed in the laboratory, while numerical research was performed using the Finite Element Method (FEM).

The interaction of panels and frames has been shown [8] to be crucial for overall rigidity and load-bearing capacity. For the epoxy bond, it was found to be rigid and to provide a full composite bond between the frame and the glass panel - the load-bearing capacity is high and the ductility is low. It is completely different with polyurethane (or silicone) adhesives. The bearing capacity is stretched relatively quickly, the adhesive is stretched and the composite bond is broken, so the bearing capacity is significantly lower.

This paper shows the possibility of applying a stiffening system based on glass or plexiglass and gives the concise overview of what was examined in a case study of a specific architectural object [9]. A computer model of the general structural system of the building was created, with special reference to the separated mass (subsystem) of the structure, which is sensitive to seismic influences - the dome on eight pillars, at the top of the building, where the height of the dome is +48.00 meters, measured from the elevation of the terrain around the building. The diameter of the dome is basically 16 m, and there is also a small dome on the dome.

In the first stage of the analysis, the calculation based on the Finite Element Method simulates the exposure of the general structural system to seismic force, in accordance with applicable regulations for the design of buildings in seismically active areas [10]. By analysing the behaviour of the general structural system, the problems of insufficient integration of the separated mass of the structure have been identified, which are reflected, above all, in the high values of deformations.

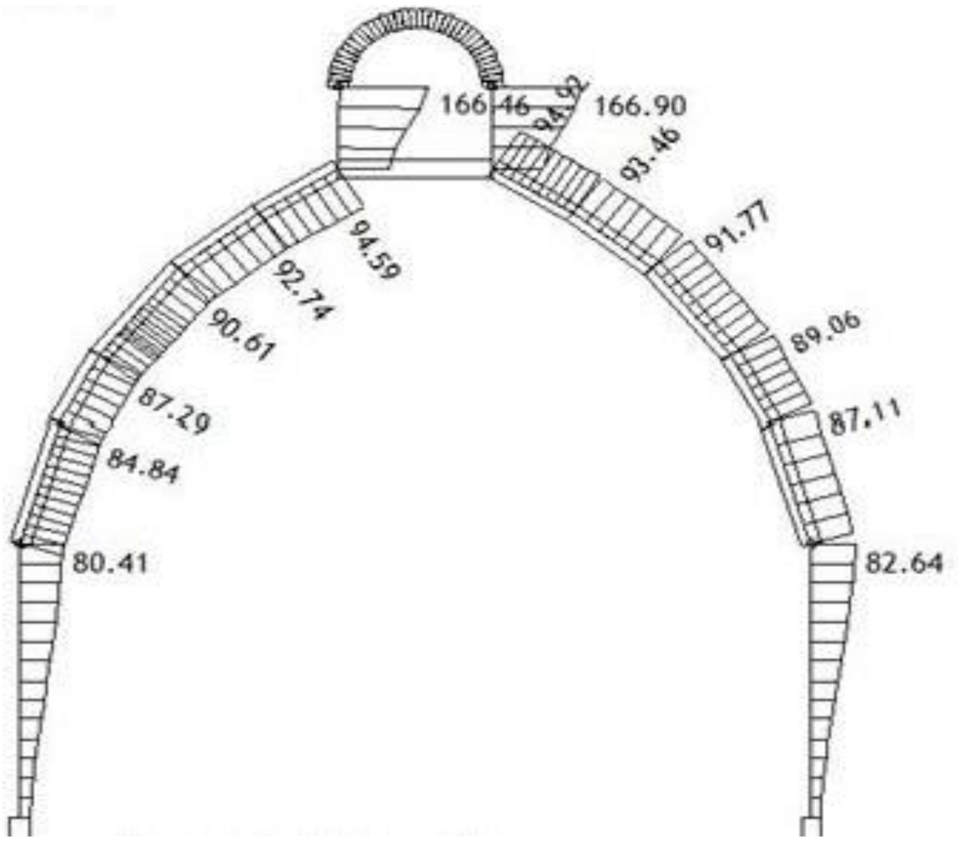

Figure 1: deformation of the entire dome in the horizontal directions

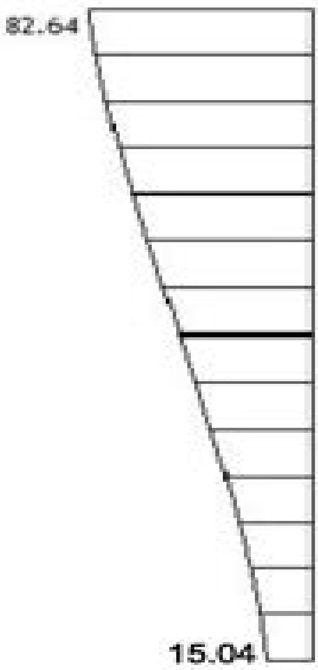

Figure 2:separately shown deformation of one of the eight pillars on which the dome rests

It can be noticed that the displacement of the base of the pillar is only 15.04 mm, which is also the displacement of the top of the basic body of the building. Then the relative displacement of the dome cornice will be:

$H_{p,vk,rel}$ = 82,64 – 15,04 = 67,60 mm

This further means that the relative displacement of the cornice of the small dome, in relation to the base of the main dome, is:

$H_{p,mk,rel}$ = 166,90 – 15,04 = 151,86 mm.

These results show very high values of the displacement of the top of the object caused by the earthquake. The dome, as a reinforced concrete shell, together with the edge ring beam, represents a significant inertial mass for the action of horizontal (seismic) forces. The constructive system of the dome, due to the action of seismic forces, behaves largely independently and asynchronously in relation to the object, while representing its integral part. It is necessary to find a solution that will reduce the displacements to an acceptable level and that will, above all, integrate the constructive system of the dome into the constructive system of the rest of the building.

THE SOLUTION OF ASEISMIC STIFFENING

In the second stage of the analysis, elements of seismic stiffening of the structure, in the form of a panel of structural plexiglass, were applied to the same computer model. The efficiency of the applied solution was examined by calculating the construction with stiffening and analysis of the obtained results. Thus, the integration of the dome structure with the rest of the structure of the building is achieved by the structural plexiglass and steel frame. Structural plexiglass is placed in the glazed surfaces of the existing glass facade of the dome, instead of the existing glass membrane. The existing glass membrane is made in a classic way: black steel made of slender profiles forms a network - a “grill”, i.e. a facade division, in which windows made of ordinary window glass, 3 to 4 mm thick, are placed.

The term structural plexiglass refers to the plexiglass that has a (unconventional) bearing role on the facade, and not just the function of partitioning the inner space from the outer, with the default transparency. In that sense, "structural" means bearing, as opposed to the usual meaning in building or concrete structures, where a similar word "constructive" is often used for non-bearing elements, which are then constructively reinforced.

Structural plexiglass has a thickness of d_{st} = 60 mm and is composed of shafts measuring 400/500 mm. Plexiglass is housed in a steel grill, which consists of 9 horizontal bars and 11 vertical bars of "T" cross-section. Each horizontal bar has a polygonal longitudinal axis so that the axis is inscribed in the shaped surface of the transparent facade. The vertical steel bars of the grill are at an axial distance of λ_{ver} = 420 mm, and the horizontal bars are at an axial distance of λ_{hor} = 520 mm. The edge profiles of the steel grill are rigidly connected to the concrete structure on which they are supported along their entire length, so that they are tipped with dowels, and the dowels are at a mutual distance of λ_m = 300 mm.

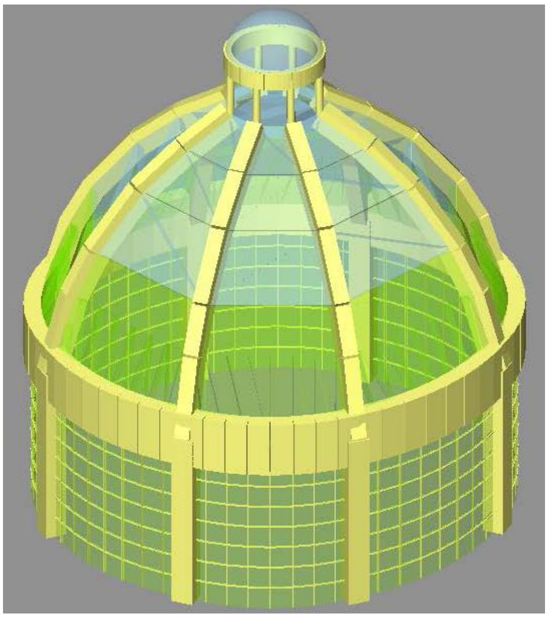

Fig. 3 "Rendered" computer model of the dome, with applied stiffening in the form of a panel of structural plexiglass

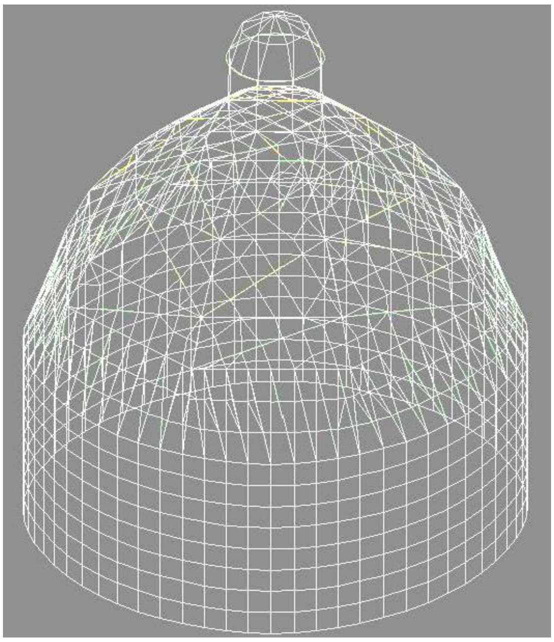

Fig. 4 Computer model of the dome with a visible network of finite element

The described system, which consists of a steel frame - grill - which houses 80 shafts of structural plexiglass, which together make a "mosaic" size 4200/4400 mm in frontal appearance, fills all eight fields between the pillars of rectangular cross section on the dome facade. Each plexiglass window is rigid in its plane, and by means of a steel frame, together with the adjacent windows, it forms a rigid shaped surface, continuously rigidly connected to the existing structural concrete elements of the dome. In this way, the construction of the dome becomes a unique rigid system, consisting of:

- existing concrete structures (eight pillars of rectangular cross-section, annular beam of rectangular cross-section along the top of the pillars at the height of the dome cornice);
- a steel grill that corresponds in geometry and division to the existing facade locks of the dome facade;
- Structural plexiglass of rectangular segments, which in shape correspond to the existing glass windows on the facade of the dome.

Previously analysed computer model, was then completed with plate elements - windows made of structural, laminated plexiglass. Physical and mechanical characteristics of laminated plexiglass are defined in the material base and as such are associated with plate elements in the computer model. Previously, precise data on the physical and mechanical properties of laminated plexiglass were obtained through laboratory tests.

ANALYSIS OF THE RESULTS OF ASEISMIC STIFFENING

In order to determine the effect of introducing structural laminated plexiglass elements into the dome structure, the performed computational analysis is completely analogous to the previous one. The modal analysis was conducted through six tones, so that its results could be used for seismic calculations. By comparing the results of two modal analyses, it was determined that the application of structural laminated plexiglass in order to stiffen the structural system of the large dome and its integration into the structural system of the rest of the building, achieved full effect.

The effects of the use of structural laminated plexiglass were investigated to the end, by checking the impact of its application on the values of the displacement of the top of the large dome. For that, analogous to the analysis of the original model, a seismic calculation was performed, according to the same criteria as in the first case (I category of the object, VIII seismic zone, construction type 4).

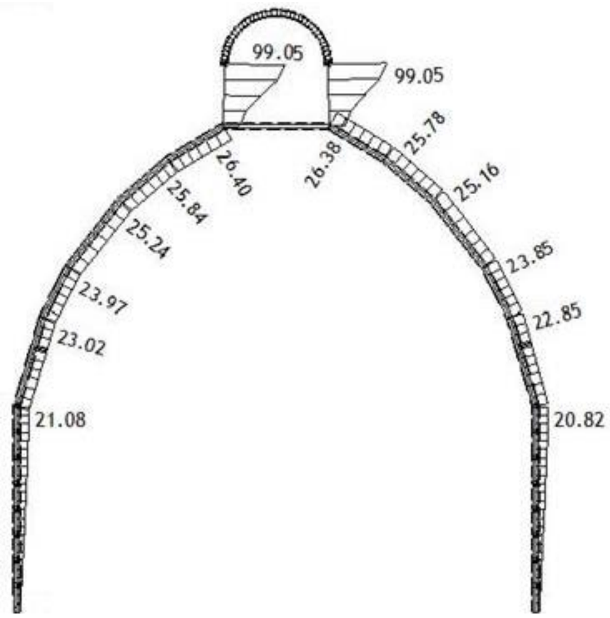

Fig. 5 Deformation of the whole dome after stiffening

The parameter that shows how much effect the application of large dome stiffening has in the form of structural plexiglass is the magnitude of the relative displacement of the dome cornice in relation to the dome base, and this parameter has the value $H_{p,vk,rel,1}$ = 14,79 mm. If the value of this parameter is compared with the value of this parameter from the model without stiffening, we get:

$H_{p,vk,rel} – H_{p,vk,rel,1}$ = 67,60 mm – 14,79 mm = 52,81 mm

Expressed as a percentage:

$(H_{p,vk,rel} – H_{p,vk,rel,1} / H_{p,vk,rel}) \cdot 100 = (52,81 / 67,60) \cdot 100 = 78,12\%$

This means that, in the case of seismic forces in the "X" direction, the effect of stiffening the dome with panels of structural plexiglass, reducing the horizontal displacement of the dome in percentage is as much as 78.12%.

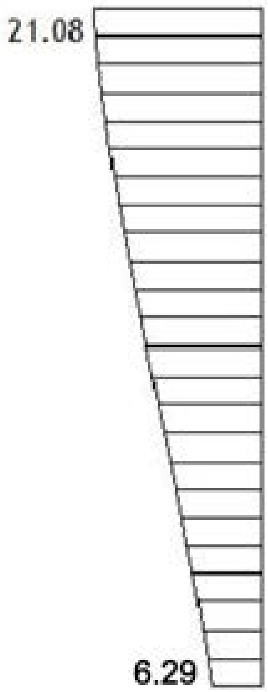

Fig. 6 Deformation of one pillar after stiffening

In the computer model of the dome, the boundary conditions between adjacent structural plexiglass panels are set so that there is no transfer of bending moment from one panel to another, due to the fact that each structural plexiglass panel is hinged to the steel frame. The structural plexiglass panel is a filling, which receives the load exclusively parallel to its plane. In this way, by means of the limiting conditions of releasing the moment M1, the bending moment around the longitudinal axis of the contact line of the two structural plexiglass panels, the joint connection of two adjacent structural plexiglass panels was calculated. This way of modelling the longitudinal connection of two adjacent panels allows to transfer from one panel to another all the forces parallel to the planes of the panel, but do not transmit bending moments caused by possible load that is perpendicular to the panel plane.

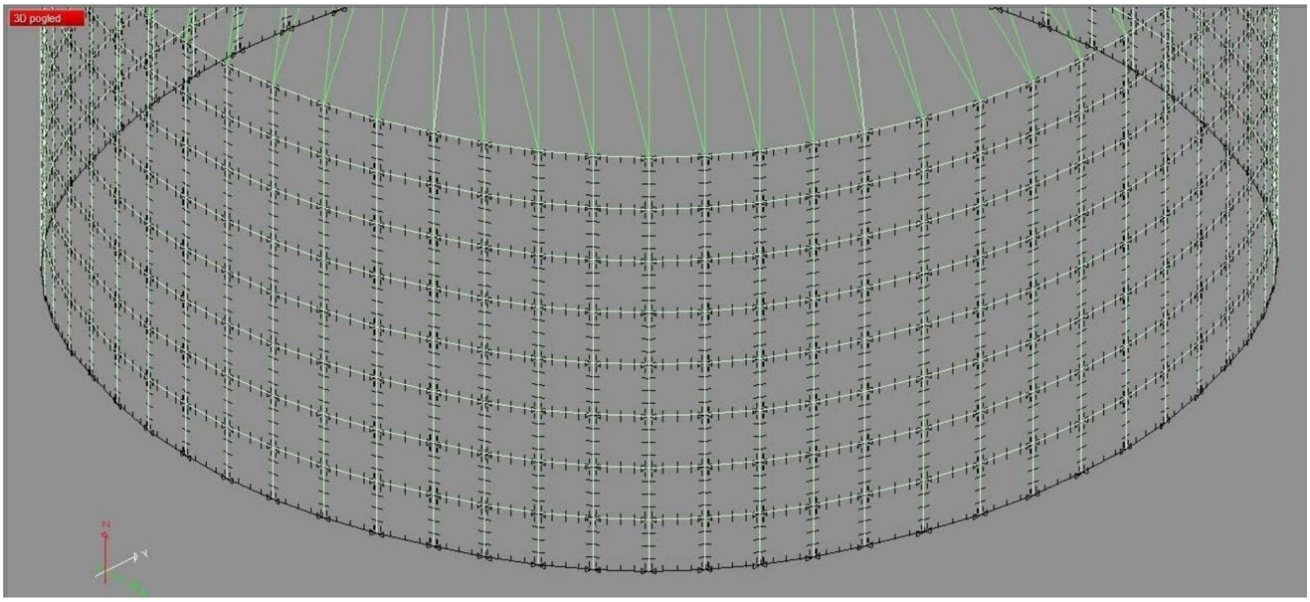

Fig. 7 Facade surfaces of the dome in a computer model; symbols with short black lines represent hinged connections along the edges of individual structural plexiglass panels

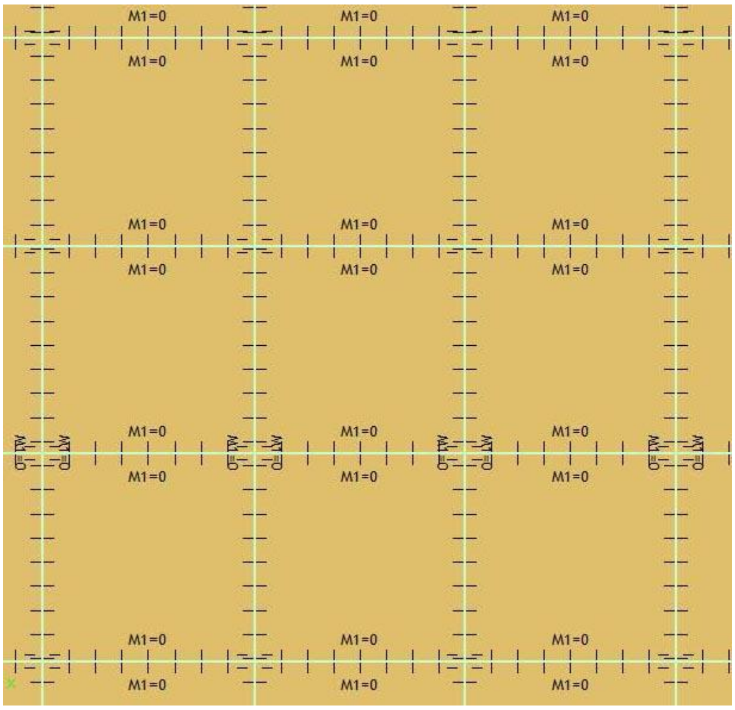

Fig. 8 Separate segment of the façade surface of the dome, which shows the division - detail of the boundary conditions along the overlap of the plate elements on the grill rods; the torque "M1" around the axis "1" is not transmitted from one plate element to another ("M1 = 0")

Previously, through the presentation of computational analysis, the rate of deformation reduction was checked, as a direct effect of stiffening the large dome with the help of structural plexiglass panels. The reduction of deformation is so much that it fully confirms the effectiveness of this type of stiffening. However, in addition to the displacement values, it is necessary to check the values of the main stresses that occur in the cross section of the structural plexiglass panel, whose thickness is 60 mm, and which serves as an seismic stiffening. The main stresses in the diagrams are calculated and shown only for the upper and lower side of the plate element, where the values of shear stresses from transverse forces are equal to zero, so that the stress image for complex stress fully corresponds to the flat stress state.

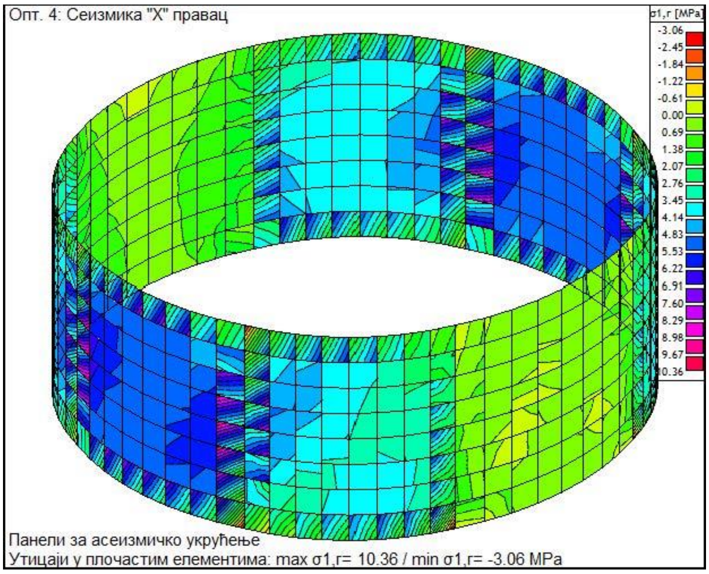

Fig. 9 Values of the main stresses on the upper edge of the laminated plexiglass slab elements, in the façade surface for the "H" direction of the earthquake

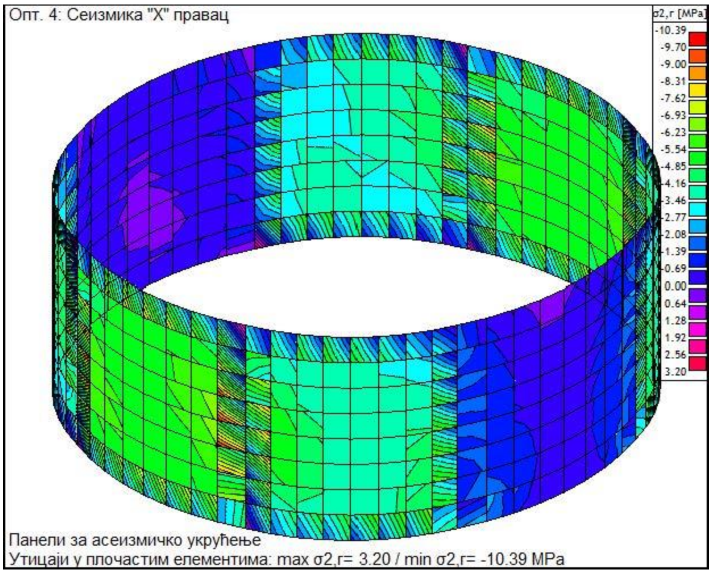

Fig. 10 Values of the main stresses on the bottom edge of the laminated plexiglass slab elements, in the façade surface for the "H" direction of the earthquake

The computer model was created as part of the software package for the analysis of building structures TOWER, and the complete treatment of the model was carried out using the Finite Element Method. The results in the computer model always show the inevitable but expected stress concentrations, but the essence of the results is easily recognizable and usable as a system of input parameters for laboratory testing.

EXPERIMENTAL VERIFICATION OF ASEISMIC STIFFENING SOLUTION WITH GLASS AND PLEXIGLASS

Since the case study involved the application of unconventional materials, i.e. the use of materials that are widespread and available for unconventional purposes, it is necessary to verify such a general concept of seismic stiffening of architectural structures through laboratory tests.

In the first phase of laboratory tests, the physical and mechanical characteristics of laminated glass and plexiglass were determined [11], so that the data obtained in this way in the computational analysis could be used as relevant input parameters.

TABLE I

Physical and Mechanical Characteristics of Laminated Glass and Laminated Plexiglass

Material characteristics	Laminated glass		Laminated plexiglass	
Volume mass [kg/m^3]	2300		1170	
Compressive strength [MPa]	177		122	
Tensile strength [MPa]	15		45,8	
Elasticity Modulus [GPa]	68		3,8	
Thermal expansion coefficient [1 /℃]	$6{,}4 \cdot 10^{-6}$		$65{,}6 \cdot 10^{-6}$	
Bending test results				
Bending strength [MPa]	14	37	65	104
Elasticity Modulus [GPa]	42	67	2,8	3,1

In Table I, we should notice the differences in the values of flexural strength, and even the modulus of elasticity, depending on the orientation of the lamellae from which the tested sample is made. The advantages of samples in which the load is applied parallel to the lamellae are noticeable.

In the second, central phase of laboratory testing, an individual element of the structure for stiffening the dome is treated: a separate panel of structural glass or plexiglass d = 60 mm thick, dimension 400/500 mm, placed in a steel frame made of rods "T" cross section, to which the panel rests by means of a layer of hard rubber. Such a composite structural assembly was isolated as a representative sample from the rest of the structure - the façade surface of the dome - and its behaviour under the effect of dynamic loading is examined.

The load intensities applied to the isolated panel in laboratory conditions were determined on the values of the forces in the rods framed by the panels in the computer model, in the previously presented analysis. Thus, the stresses, i.e., forces obtained as a result of computational analysis, can be compared with the intensity of the force communicated according to the dynamic pattern to the experimental model of an individual structural element - composite structural assembly based on glass/plexiglass.

It was found that the values obtained by computational analysis, which relate to the stresses in the cross section of the plexiglass filling (main stresses "$\sigma_{1,2,g}$" and "$\sigma_{1,2,d}$" in plate elements), are within the limits of laboratory test results experimental models. Computational analysis has even shown that there is a significant reserve in stress utilization, if we compare its results with the results obtained in the laboratory when determining the physical - mechanical characteristics of basic materials. The positive values of the main stresses, which represent the tensile stresses, are such that they can be annulled by prestressing during the installation of the plexiglass (or glass) filling in the steel frame. Prestressing in the assembly phase is enabled by the use of an intermediate layer of rubber.

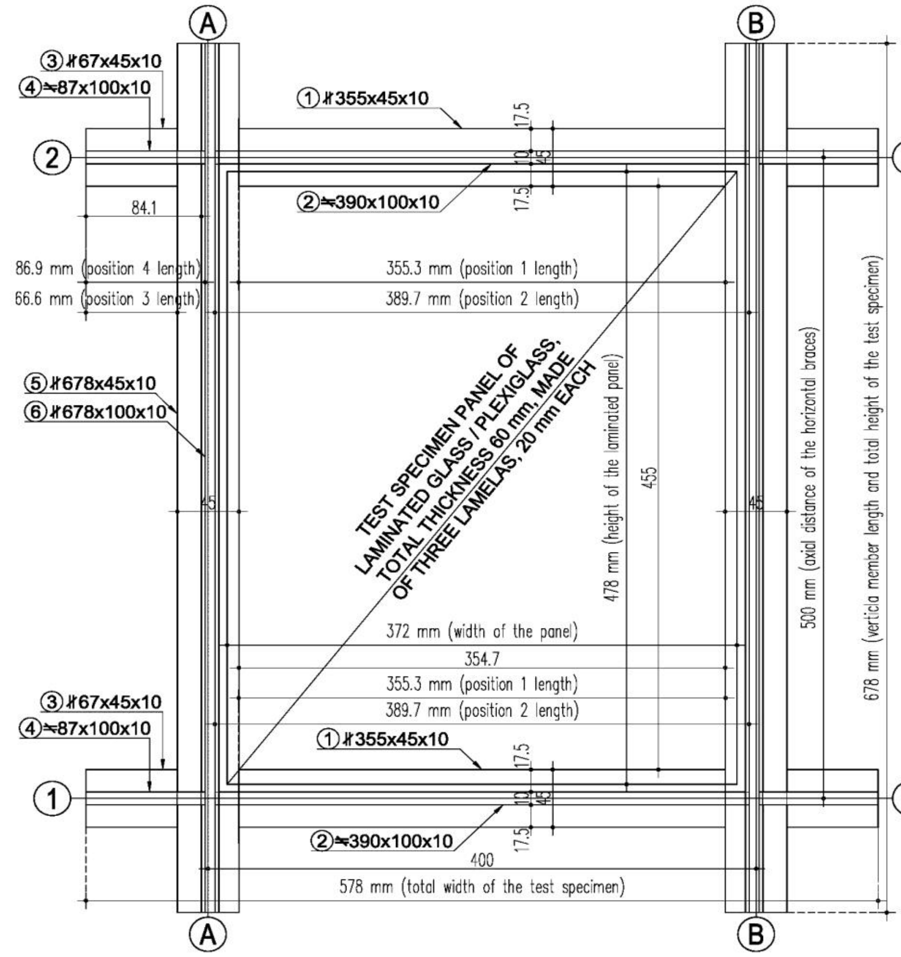

Fig. 11 Front view of the finished laminated glass/plexiglass composite panel ("inside" view)

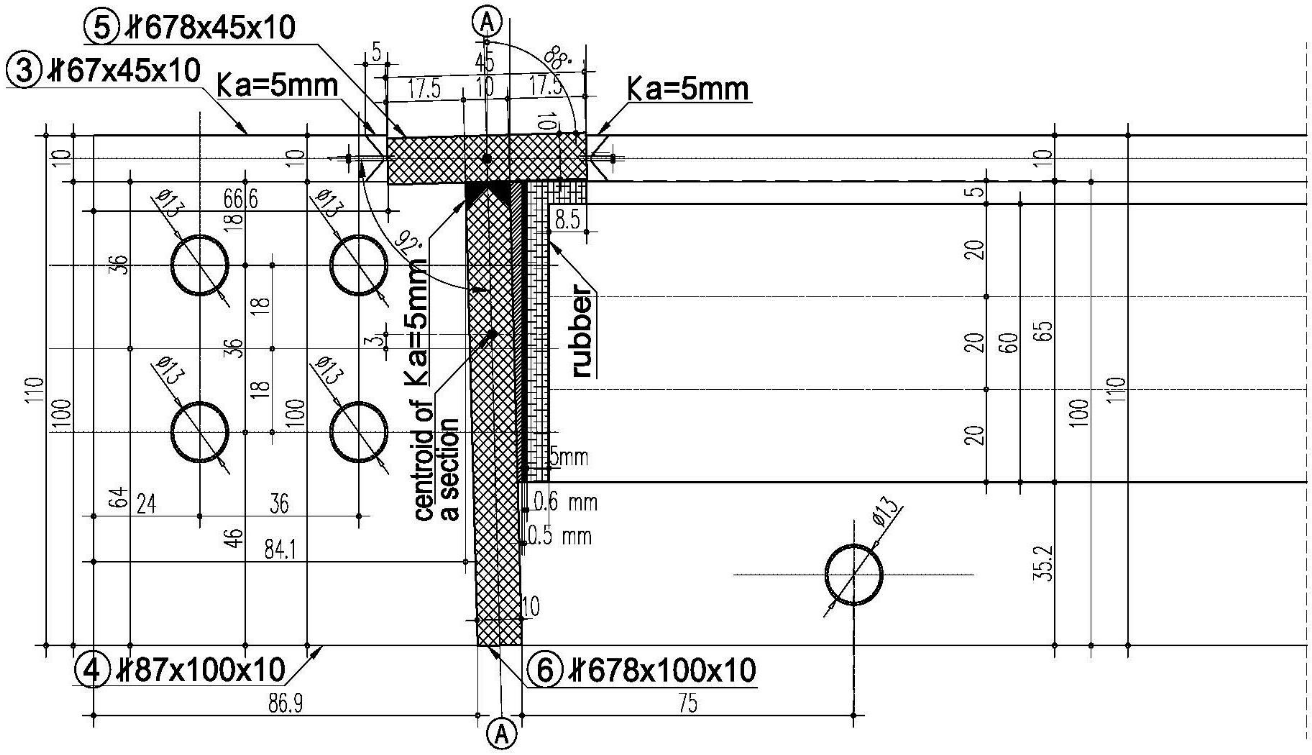

Fig. 12 Steel frame construction - horizontal section detail: first phase of laminated glass / plexiglass panel assembly

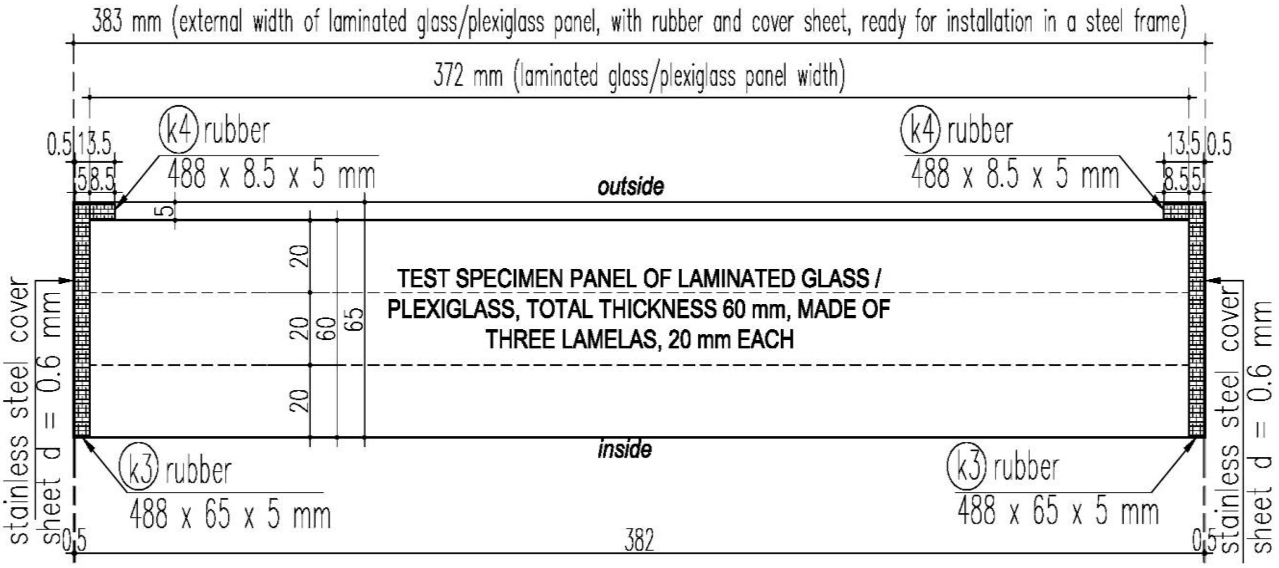

Fig. 13 Laminated glass / plexiglass infill, prepared for installation in a steel frame - horizontal section detail

Fracture of the glass filling in the composite assembly occurs when applying a force of 86 kN, and comparing the behaviour of composite assemblies based on glass and plexiglass fillings, can be seen less deformation of the panel with plexiglass filling by about 33%, as shown in the following figure.

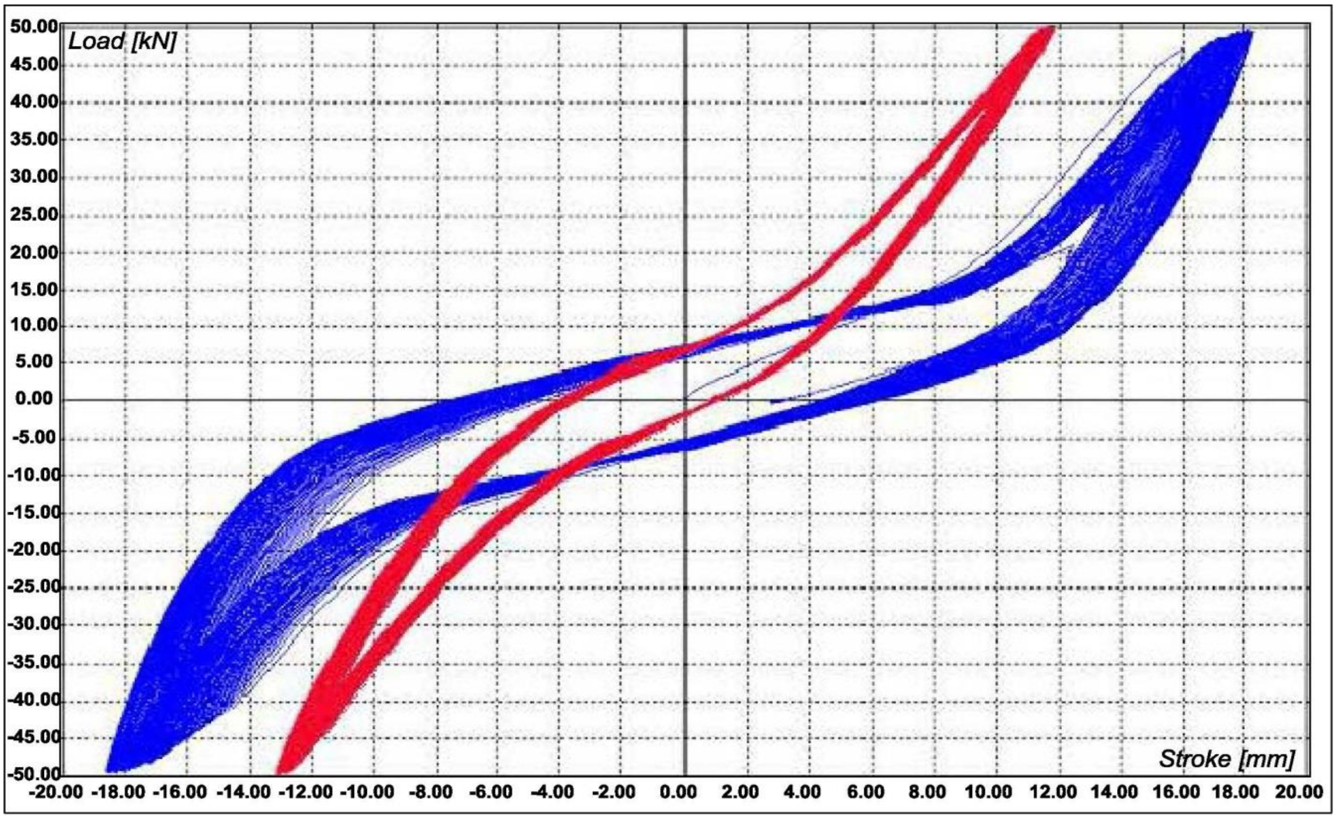

Fig. 14 Hysteresis loops from the test of panels with glass filling (blue) and plexiglass filling (red), exposed to a dynamic force of intensity 50 kN, at a frequency of 1.6 Hz

CONCLUSION

The solution of seismic stiffening of architectural objects with the help of elements filled with glass and plexiglass is presented, which was first calculated, and then subjected to experimental laboratory research, conducted on composite panels, which are exposed to cyclic loading. Composite panels are formed on the basis of laminated glass or laminated plexiglass filling. The infill is framed in a steel frame, on which it rests by means of an intermediate layer of rubber. Composite panels, which were subjected to experimental laboratory testing, represent individual elements of a wider system formed by a series of panels, whose role should be to stabilize the structure exposed to seismic loading. In this way, the classic glass facade made of slender profiles, which forms a grid (grill) in which the windows of ordinary window glass are placed, can be replaced by a grill and filling of laminated structural glass, or laminated plexiglass. The system formed according to that principle, is integrated into the supporting structural system of the object, enables its stabilization from the aspect of horizontal displacements, as well as in the sense of receiving seismic forces.

From laminated glass, ie laminated plexiglass, flat elements of the structure are formed, whose function is to stiffen the object for the action of seismic forces. Since these are materials that are most often used in construction practice for completely different purposes, it can be said that this is their unconventional use. For that reason, they were laboratory tested for the effect of the dynamic force of the parallel plane of experimental models, which determined the capacity of their bearing capacity for this type of load.

The first part of laboratory tests, with the aim of determining the physical - mechanical characteristics, showed significant differences in the properties of laminated packages, depending on the orientation of the lamellae in cross section. At the same time, the differences in the values of flexural strength and modulus of elasticity are more pronounced in laminated glass than in laminated plexiglass, which thus exhibits the properties of a more homogeneous material.

The central part of the work in the laboratory is the testing of experimental bodies exposed to dynamic loading, performed from the aspect of comparing the efficiency of two different types of fillings: laminated glass and laminated plexiglass.

In the case of assemblies with laminated glass, a higher dissipation of results is noticeable than in the case of assemblies with laminated plexiglass filling. Greater deformation of glass assemblies is a consequence of the deformation mechanism of the whole assembly. This primarily refers to the possible slippage between the rubber panel and the frame, which, due to the greater rigidity of the filling, can be expected more with laminated glass panels than with laminated plexiglass panels. At forces greater than or equal to 22 kN, the effect of reinforcement, ie increased stiffness, is present. This effect is more pronounced in glass panels than in plexiglass panels. The reinforcement effect is a consequence of the activation of the pressed diagonal of the panel when the frame and the corner of the panel come into contact with the pressed rubber, but also of the viscoelastic properties of the rubber itself. In laminated glass panels, hysteresis loops show greater energy disparity. It has been observed that per cycle with laminated glass panels compared to laminated plexiglass panels, the increase in energy dissipation is from 30% to 80%. The clearer effect of reinforcement in composite panels with laminated glass filling served to draw a conclusion about the better integration of laminated plexiglass filling into the composite assembly. In the case of laminated plexiglass filling, the reinforcement effect is much less pronounced, which testifies to the earlier activation of this type of filling within the composite assembly. If we observe the share of the filling in the force reception in the examined domain, the part of the force taken over by the filling from the plexiglass is about 58% for the force amplitude of 11 kN, about 60% for the force amplitude of 22 kN and about 67% for the force of 33 kN.

Based on the analysis of the results obtained from the laboratory testing of composite assemblies exposed to dynamic loading [12], it can be concluded that composite assemblies with laminated plexiglass filling show:

1. Better integration of the filling into the composite assembly;

2. Smaller displacements compared to laminated glass fill assemblies.

In addition to forming a grill of certain stiffness, the presented composite panels enable the introduction of additional damping into the construction system. Damping is primarily realized through the dissipation of energy in the intermediate layer between the filling and the frame, in which the decisive role is played by rubber, through which the filling (laminated glass / laminated plexiglass) rests on the steel frame. The function of damping, i.e. depreciation, is realized by the intermediate layer of rubber with a defined degree of hardness. Laboratory tested experimental models based on laminated plexiglass, in the case study were presented through a computer model, as elements of the construction of an architectural object.

The case study was performed through a complex computer model of building construction, created in a specialized software package, which is based on the Finite Element Method. In the computer model, the properties of composite panels previously tested in the laboratory, as well as their relationship with other elements of the structural system of the building, are described through physical - mechanical characteristics and boundary conditions.

The results obtained by analysis through a computer model, show the efficiency of stiffening the structural system using a system of composite panels filled with plexiglass. The efficiency of stiffening is, above all, reflected in the form of:

1. Changes in the modal characteristics of the analysed object;

2. Reduction of displacements caused by seismic actions.

The seismic analysis was performed on the basis of equivalent static load, and the obtained forces in the structural elements created according to the experimental models are within the values from the laboratory test. This shows that the bearing capacity of the experimental model, expressed in laboratory conditions, can be sufficient to receive the corresponding part of the seismic force in the real structure.

The analysis of the computer model, first of all, checks the intensity of forces and stresses, according to the criteria that are also defined in the examination of the experimental model. It is necessary that the forces and stresses are within the limits of the results of laboratory tests, and at the same time the structure is effectively stiffened, in terms of changing (improving) modal characteristics and reducing deformation. The analysis of the computer model and laboratory tests in the presented procedure of designing seismically resistant architectural structures, give a new concept of application of unconventional materials.

The presented research contributes to the design of seismically resistant architectural structures, by defining the concept of seismic stiffening using a laminated glass / plexiglass infill, framed in a steel frame. The concept includes the formation of an efficient composite assembly, in which each of the elements of the assembly has a role in the reception and treatment of seismic force. The infill (laminated glass / laminated plexiglass) absorbs most of the seismic force and reduces the deformation of the entire structure, the steel frame frames the stiffening system and integrates it into the global structural system of the object, and rubber performs the function of damping - depreciation. Such a solution could be very applicable where no other intervention is possible, in terms of the obligation to preserve the aesthetic values of the building, which primarily refers to cultural and historical monuments, or any type of building under some kind of protection, all in terms of preventive restoration.

Then the conversion of existing surfaces with glass can be reported - from the function of partitioning the space, to the function of structural load-bearing capacity, or, possibly, new (load-bearing) surfaces made of glass / plexiglass can be introduced. This makes the secondary non-bearing elements into load-bearing elements.

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