3D ANALYSES OF TIMBER STRUCTURES

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Summary

The paper presents three examples of 3D modelling and analysis of spatial timber structures. The analyses were conducted by means of COSMOSM software at the Faculty of Civil Engineering, University of Zagreb (Croatia).

3 D spatial modelling provides a better view of the status of stresses and deformations for various loads as well as a view of the spatial stability of the entire 3D system by means of buckling analysis. A comprehensive library of finite elements of COSMOSM ensures detailed modelling of connections. It is also important in the analysis of timber structures to take into account the orthotropic characteristics of timber providing a more accurate view particularly of the status of stresses perpendicular to tensile zone.

In the presented examples, planar simplifications of the structural analysis are mostly impossible.

1. Introduction

Complex structural analyses are currently made possible by a number of high quality and reliable software applications. In such circumstances, planar structural modelling has no longer its purpose as in the end each structure is a spatial structure, regardless of our concepts based on the past and attempts to simplify the analyses due to the lack of contemporary computer aids. Computer technology has developed to such extent that it is relatively simple to encompass all real situations in the structure and transfer them into the analysis model. Then we speak of complex modelling.

COSMOS/M is an example of a program with an extensive library of finite elements making possible such complex modelling, where we can realistically obtain the values of stresses, deformations, stability, oscillation modes, dynamic analysis, etc. for linear and non-linear analyses. That is only part of the options of interest for us in the analysis of timber structures. More information on the options provided by this software package is available at www.srac.com or www.cosmosm.com.

From a wide range of offered finite elements, the following are most frequently used in timber structures:

- TRUSS3D spatial element connecting two points, has three degrees of freedom per node
- BEAM3D spatial elastic beam element also connecting two points and having six degrees of freedom per node (3 rotations and 3 translations)
- SOLID spatial elements have 8 points per element. Each point has three translation degrees of freedom, and one degree of freedom per node for thermal analyses.
- SHELL elements, most frequently used SHELL3L or SHELL4L elements, as they make possible the orthotropic modelling in timber structures. These elements make possible modelling up to 50 layers. Modelling of membrane and bending behaviour is possible. Per each point of element, there are six degrees of freedom (3 translations and 3 rotations).
- SPRING elements have one, two or three points. They may have longitudinal, transversal or rotational stiffness. Transversal stiffness is impossible in elements with one point. We most often used 2 node elements.

- RBAR elements are elements with two points acting as a solid body. The element has up to 6 degrees of freedom per node depending on the elements connected to those elements. They cannot be used for buckling analyses.
- GAP elements are elements connecting two points for contact analysis problems. They act similar to a solid connection accepting compressive or tensile stress normally on the contact surface.

The paper presents three cases of complex COSMOS/M modelling of timber structures on recently constructed facilities in Croatia.
In the first case, two floors have been added to a two-floor building, with glulam structure selected for the bearing structure. The floor structure of the newly added fourth floor was made as composite structure of main glulam beams and reinforced concrete slab. Timber and concrete were connected by steel dowels.

The second example is a complex spatial structure of a tennis hall covering a tennis court in Kraljev vrh near Zagreb.

The third example is the presentation of the analysis of a specific spatial roof structure covering a new church in Sesvetska Sopnica near Zagreb.
All the numerical analyses have been done by means of COSMOS/M software version 2.85 or 2.9, and since recently we have been using the most recent version 2.95.

2. Annex to the Croatian Telecom building in Zagreb

The existing two-floor building required the annexing of two floors. After the analyses of the existing building, a lightweight timber structure was selected as the optimum solution, provided that a composite reinforced concrete slab with timber beams was planned for the third floor. The external walls are made of lightweight composite aluminium in combination with insulation and ISO glass of high thermal quality. The roof is made of corrugated sandwich filled with thermal insulation. Such choice of mostly lightweight materials for the structure resulted in minimum interventions on the reinforcements of the basic structure. The complex analysis model is presented on Fig. 1.

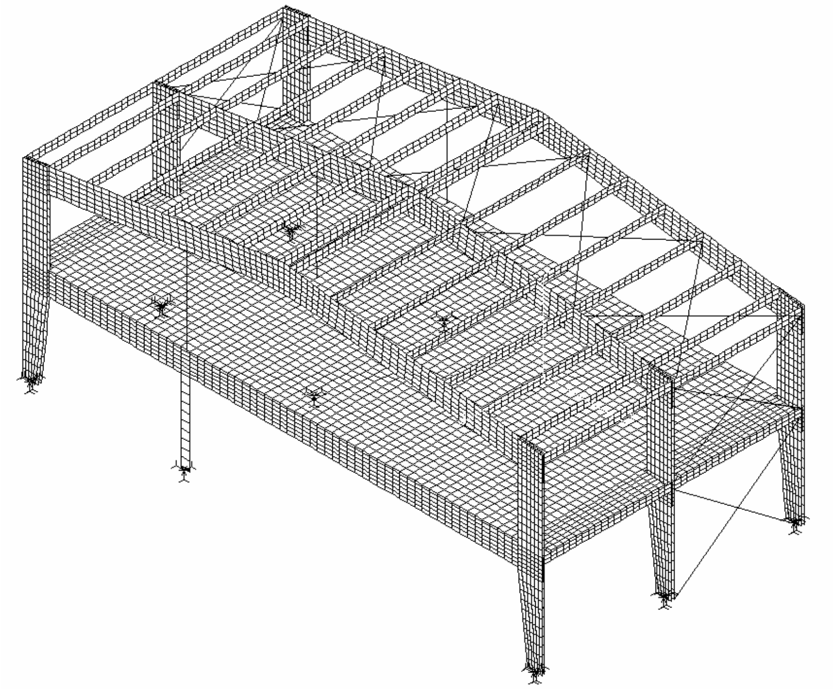

Fig. 1 *Complex model of part of the annexed structure of Telecom building in Kruge, Zagreb*

SHELL4L, TRUSS3D, SOLID, BEAM3D and RBAR elements were used for modelling. Glulam beams were modelled by means of SHELL4L elements. Columns were two-part and spaced by the axial dimension of span between elements. Width of glulam beams is taken as thickness of elements with real values. The static system consists of double-pitched frameworks with beam connection element at the third floor level which a composite reinforced concrete slab is connected to. The main span is 16.80 m, and the interval between beams 4.33 m. Thickness of reinforced concrete slab is 7 cm.

Fig. 1 shows border conditions of retention for the existing reinforced concrete structure, by joint connections with prevented three shifts. Two fields have been modelled in order to obtain real status of stresses on the medium glulam element.

Specially modelled is the angular connection of glulam elements of double timber columns with single-part element of glulam cross beam, in order to obtain the real stresses in the connection by modelling of steel dowels by means of BEAM3D elements.

The reinforced concrete slab has been shifted by 2 mm from glulam beams, and the steel dowels for connection have also been modelled by means of BEAM3D elements.

Fig. 2 presents the results of displacements, and Fig. 3 shows the results of oscillation analysis, first mode of analysis presented only for a composite concrete slab with a glulam beam.

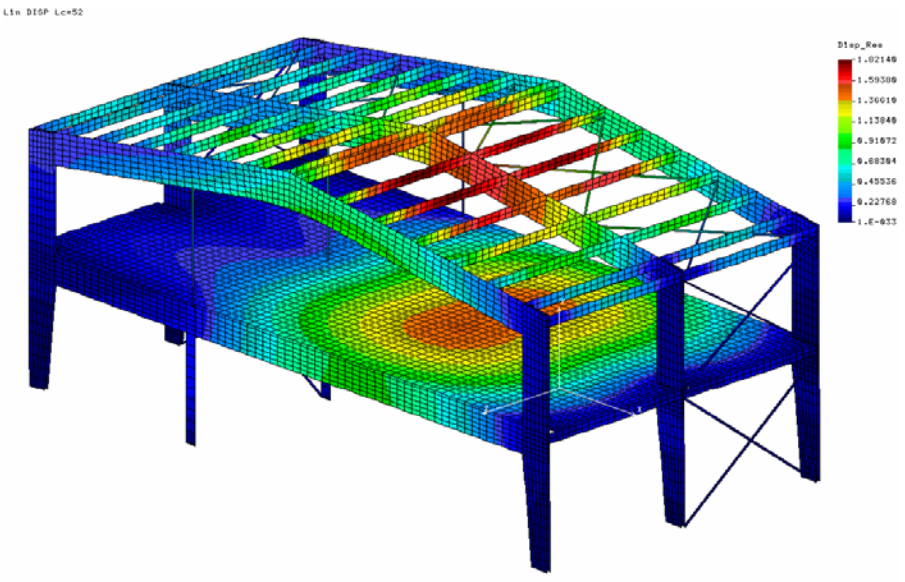

Fig. 2. *Results of displacements. For maximum loading combination.* $u_{max} = 18$ *mm*

For comfortable use of the structures intended for human habitation, oscillation frequencies should exceed 8 Hz.

Oscillation analysis of this composite reinforced concrete slab with glulam structure has shown the first oscillation mode of 9.15 Hz which is a satisfactory value.

Such analyses are required also in modelling the entire assemblies of pedestrian bridge structures where in order for comfortable movement along the bridge it is desirable to have a frequency higher than the recommended value of 8 Hz.

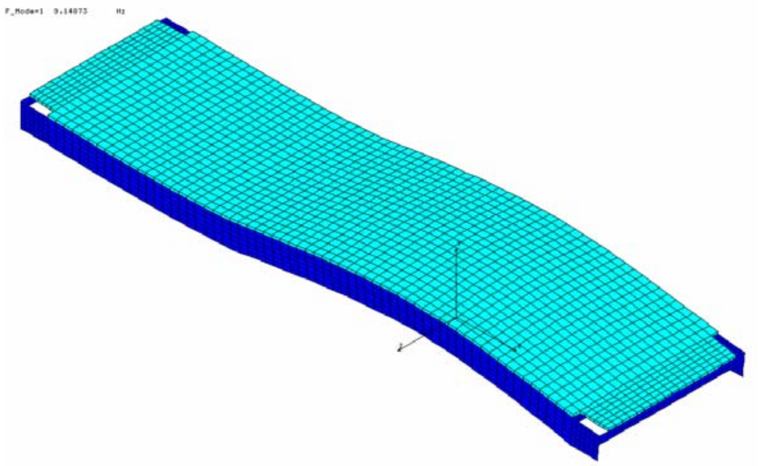

Fig. 3 *First oscillation mode of composite reinforced concrete slab with glulam beams*

The project and its implementation took place in 1999 and 2000.

3. Glulam Structure of a Tennis hall near Zagreb

An interesting solution of a spatial modelled structure is a tennis hall in Kraljev vrh near Zagreb.
At the existing sloping ground, the tennis court was constructed and the owner wanted to cover it with an independent glulam structure. On the one side, there was a 2.5 m high supporting wall, and on the other side was a tennis court at the level of the surrounding ground. In such circumstances, the best solution was a timber structure as presented on Fig. 4. The structure is analysed in spatial (3d) model from the level of new reinforced concrete columns on altitude +2.5 m.
The static system consists in double pitched frameworks with articulated columns, from which double-pitched frameworks are different symmetrically to the cross-section of the tennis ground. Spans are 18.5 m, and total length of hall is 36.60 m.

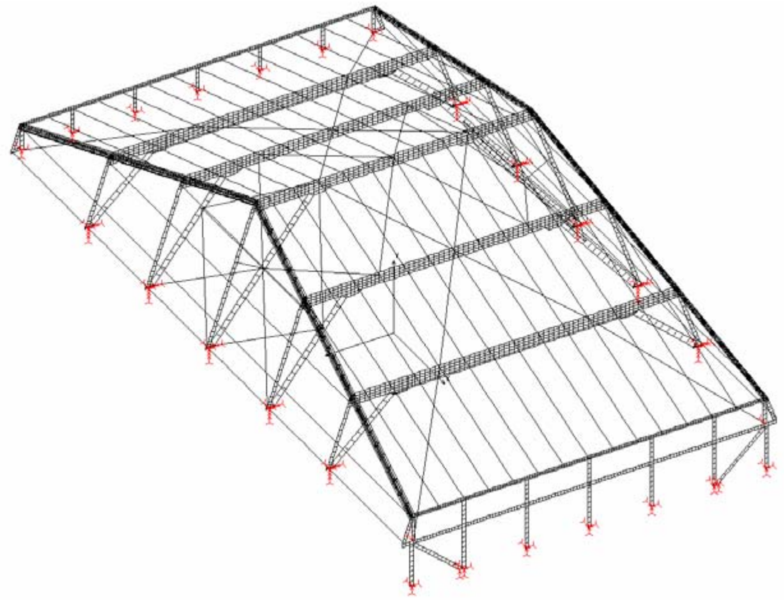

Fig. 4 *Spatial model of timber structure of Kraljev vrh tennis hall*

In the modelling of this structure, SHELL4L, SHELL3L, BEAM3D, SHELL, SOLID, RBAR, GAP and TRUSS3D have been used. Material characteristics of timber are provided with orthotropic characteristics of timber from available sources and data obtained by tests in the Laboratory of Engineering Mechanics of the Faculty of Civil Engineering of the University of Zagreb.
Following timber characteristics in MPa and density - DENS in N/mm^3:

```
MPLIST,1,2,1
  Label    Name   Temp/BH_Cr        Value
    1        EX            0     1.150000e+004
    1        EY            0     6.000000e+002
    1        EZ            0     4.500000e+002
    1      NUXY            0     2.700000e-002
    1      NUYZ            0     6.000000e-001
    1      NUXZ            0     3.300000e-002
    1       GXY            0     6.000000e+002
    1       GYZ            0     6.000000e+001
    1       GXZ            0     6.500000e+002
    1      DENS            0     4.000000e-006
    1  PERMIT_R            0     1.000000e+000
    1   MPERM_R            0     1.000000e+000
```

In addition to the main elements, secondary purlins have been modelled as well as bonds for structural stabilisation. Fig. 5 presents the status of stresses of timber elements on the deformed form for maximum load permanent + snow, and Fig. 6 presents the analysis of lateral stability of the entire system.

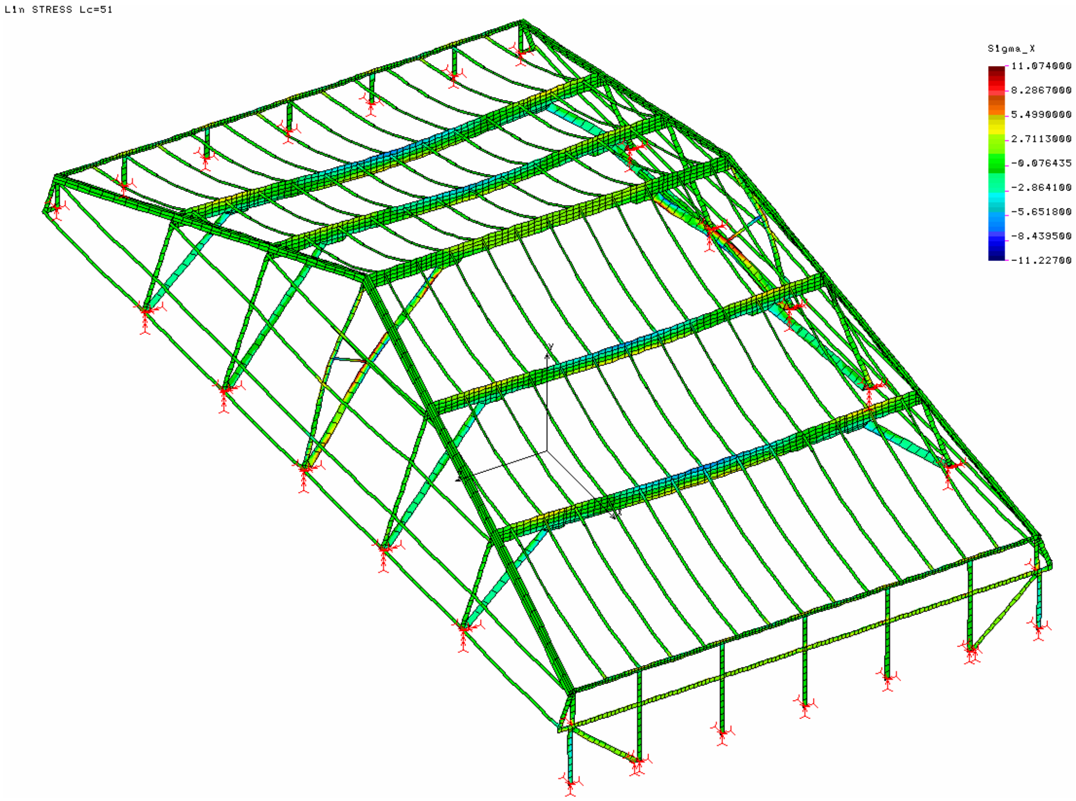

Fig. 5 *Status of stresses of only timber elements, SIG-X_{min} = -11.2 MPa*

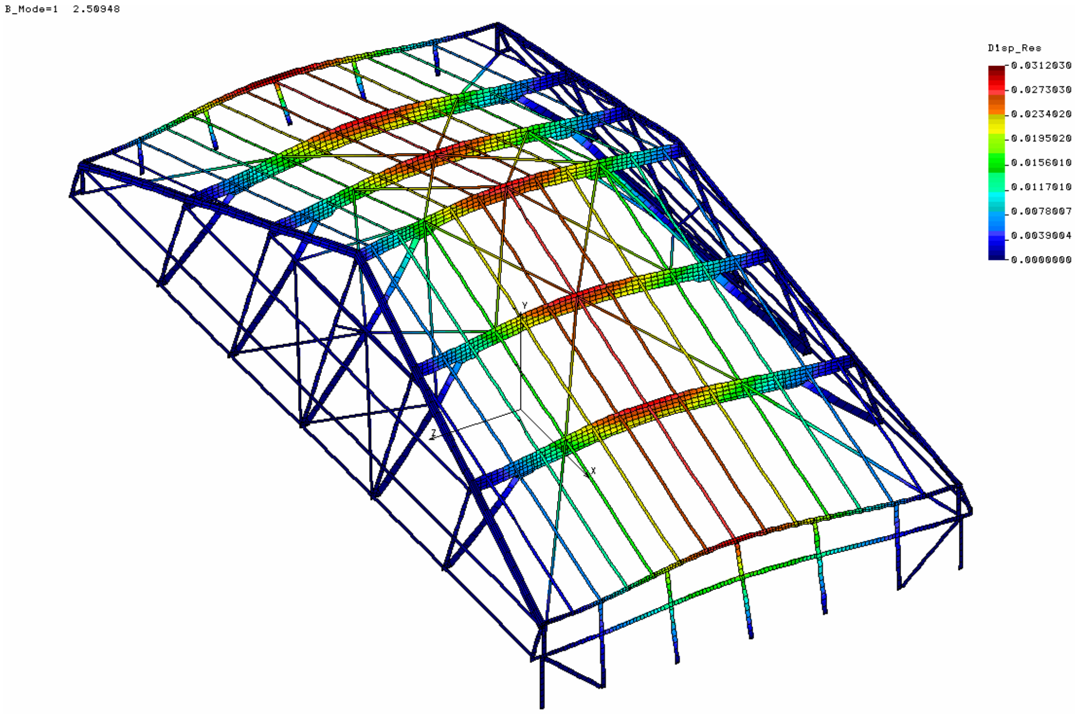

Fig. 6 *Buckling analysis of the entire model for maximum load combination*

Buckling analysis has shown that the structure has a satisfactory safety factor exceeding 2.5. Additional safety lays in the fact that the roof structure is made by OSB plates nailed on sub-structure of glulam timber purlins and forming a hard surface.

The hall made in 2001 is presented at Photo 1.

Hot welded multilayered POLIFLEX cardboard is placed on OSB roof plates from the outside.

On sloping sides, there is a translucent LEXAN cover providing sufficient light for the hall.

The existing ground in the hall is replaced by asphalt base which significantly reduces humidity in the hall.

The hall has thermogen heating by means of hot air blowing in.

Photo 1 *TennisHall in Kraljev vrh*

4. Glulam roof structure of the church near Zagreb

A variety of a specific glulam structure is the timber roof of the church in Sesvetska Sopnica near Zagreb. The lower part of the church is made as reinforced concrete structure. The roofing surface could have been made as reinforced concrete, steel or timber structure. It came out that the most simple and the cheapest solution of the roof surface was a timber structure.

The church ground plan is single axial symmetrical ovular form of 4 different semi-circular radiuses.

The roof structure consists of beams of glulam elements over which are placed horizontal timber rounded elements along the horizontal surface iso-lines.

Such sub-structure is planned to be lined with timber plates from the inside and waterproof OSB plates from the outside.

External OSB plates are covered with copper sheets.

COSMOS/M (3D) model of the bearing structure without external surfaces of SHELL4L elements is presented on Fig. 7.

In the upper part, there is a large light well of approx. 100 m^2, planned as steel grill substructure supported on the beams of ovular conical structure.

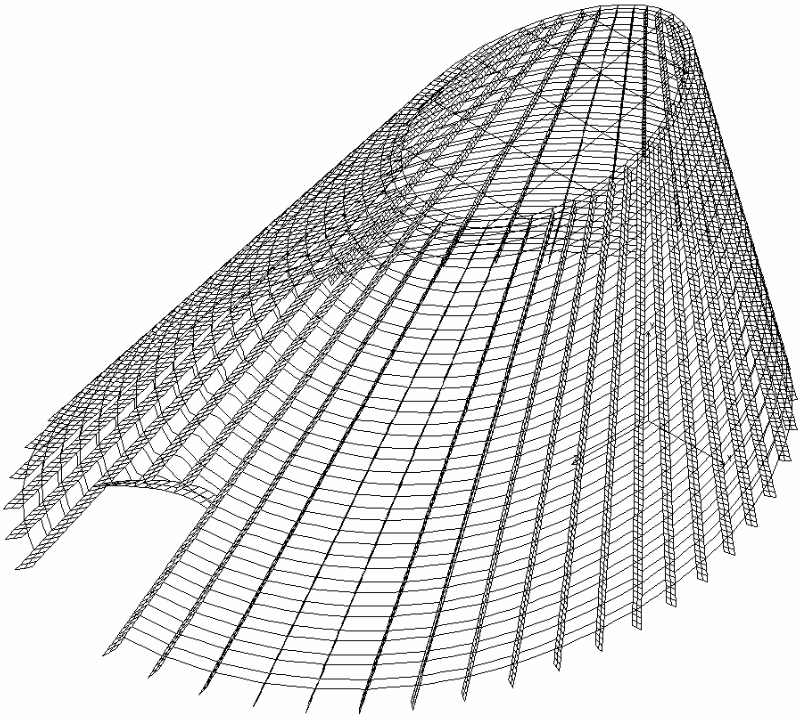

Fig. 7 *Analysis 3D model of timber church structure*

Inside the walls, based on the parallel construction system, there is 15 cm mineral wool thermal insulation.

The analysis is conducted with the following finite elements: SHELL4L and BEAM3D. By means of SHELL elements, glulam beams are modelled along the beams of the truncated ovular cone, as well as the external and the internal surface lining the substructure and forming the entire bearing structure. On spans of approx. 90 cm along the horizontal iso-lines are modelled BEAM3D elements forming the substructure for the plates which are again modelled as SHELL4L elements from the external and internal side. Real constants (thickness) of plates are given according to actual designed thickness values.

Deformations for maximum combination of loads, permanent + snow are presented on Fig. 9 and the stresses in glulam elements of the main corrugated structure of truncated cone are presented on Fig. 8.

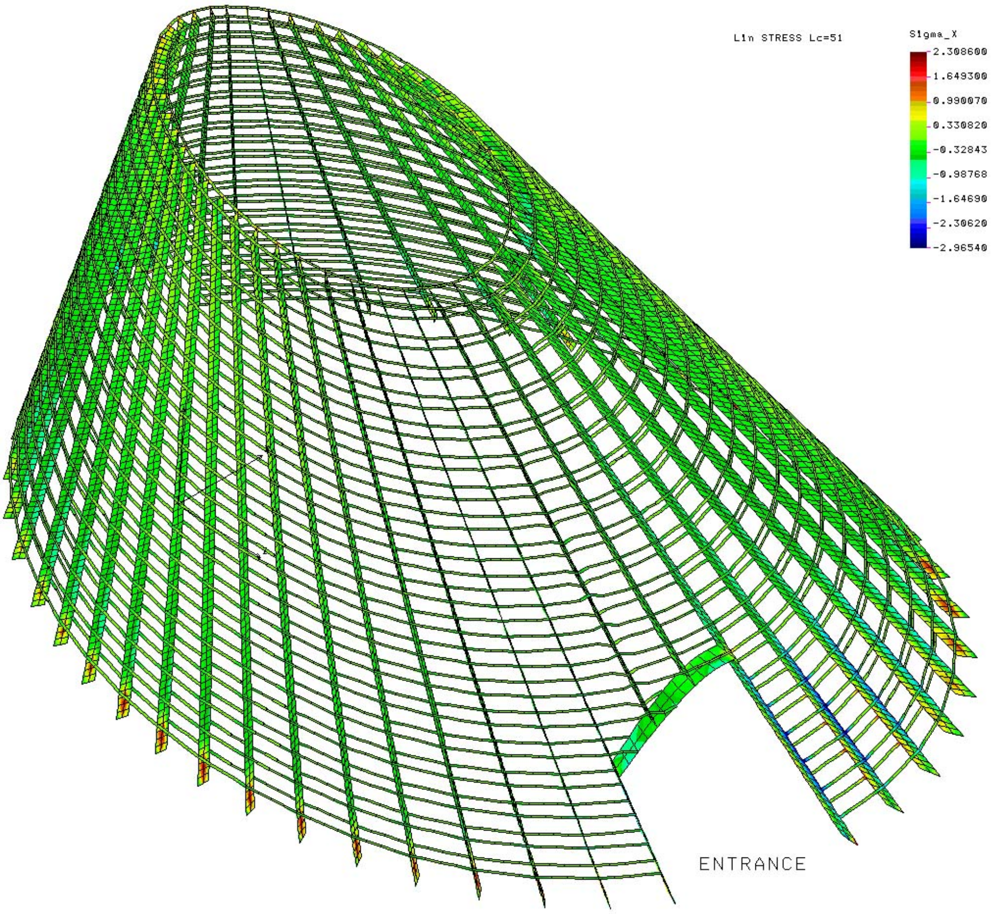

Fig. 8 *Main stresses of SIG-X glulam elements*
In the entrance zone, analytical stresses are up to -3.0 MPa

Ground floor dimensions of this structure by the main axes of symmetry are 34 x 26 m, and the height of surface is 16.0 m at the highest point.

It was interesting to analyse the behaviour of the analysis model on load from own weight in the course of making of this complex model. Until the placement of the external and internal lining, deformations were relatively high. Modelling of the entire external and internal surface provided a very rigid structure resistant to any possible load. The analytical deformation for maximum load is 22 mm.

Earthquake load is negligible as the weight of the entire roof structure is relatively small, only 96.5 t.

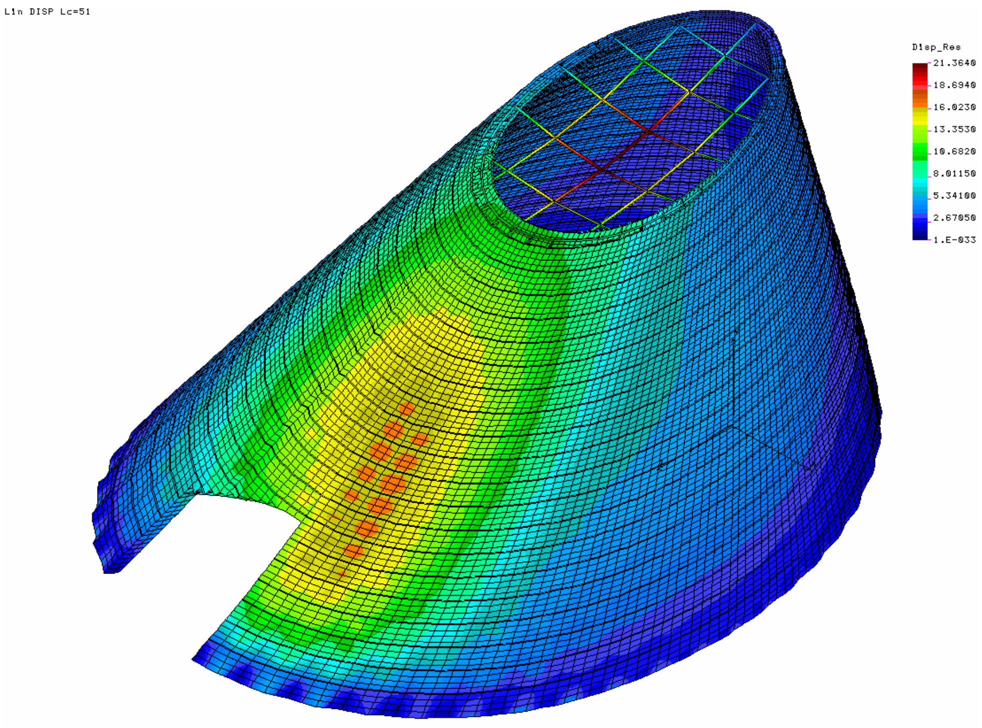

Fig. 9 *Maximum deformations of structural surface and upper steel grid structure is 22 mm.*

5. Conclusion

This paper aims to point out to the fact that the currently available software applications ensure relatively easy the complex modelling of spatial structures. Whenever possible, designers should make 3D modelling which provides a far more realistic view of the stresses, deformations, buckling, as well as oscillation modes in the linear analyses of timber structures.

Neither of the presented structures can be relatively simply transferred into planar structures for simple linear analyses. More precisely, planar simplifications of these structures would not provide even closely accurate results.

The author's experience shows that the spatial modelling may provide very good and precise results. Errors in trial tests on real models of structures are up to 20% different in relation to the results obtained on numerical analysis model. In the trial tests of timber structures, there are yields and impressions in the connections and such differences are expected.

It is however necessary to have complete knowledge of the software, particularly in the interpretation of results, because that is where errors easily occur. However, relatively high reliability in the avoidance of errors is provided by the project audit system in the Republic of Croatia, with authorized auditors performing controls of all types of structures.

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