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POINT LOADS AND EUROCODE FOR THE STRUCTURAL DESIGN OF TENSILE MEMBRANE STRUCTURES

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ABSTRACT

Tensile membrane structures have been widely used across Europe for more than half a century. While there is a standard concerning tensile membrane structures in the USA, there is not yet a design code for these structures in the European Union. European Design Guide for Tensile Surface Structures and Prospect for European Guidance for the Structural Design of Tensile Membrane Structures have already been published. Work on Eurocode for the Structural Design of Tensile Membrane Structures is underway. Once it comes into force, this standard will be connected to other Eurocodes, especially Eurocode 0 and Eurocode 1. One of the implications will most likely be the introduction of point loads to structural analysis of tensile membrane structures. However, there have been very few researches about the effects of point loads to membrane structures. This paper presents a part of the research done on the effects of point load actions to deflections of tensile membrane structures.

1. Introduction

Point loads can act on all types of structures. Nevertheless, the structural analysis of tensile membrane structures usually does not include point load actions. This is a consequence of the fact that there are no unified regulations for designing of tensile membrane structures in the European Union. In 2004 European Design Guide for Tensile Surface Structures [1] was published. It presented state of the art in designing tensile surface structures, but it was not

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intended to serve as an official standard. This Design Guide does not mention point loads as one of the possible types of loads acting on tensile membrane structures. In 2016 Prospect for European Guidance for the Structural Design of Tensile Membrane Structures [2] was published. It is a step in the process of creation of Eurocode for the Structural Design of Tensile Membrane Structures. However, Prospect, like the Design Guide, does not direct the engineers towards implementing the point load actions into the structural analysis of tensile membrane structures. It remains unclear why this is so. One of the possible explanations for this is that point load actions have negligible effects on membrane structures.

There are only a few published researches dealing with point load actions on tensile membranes. Selvadurai investigated deflections of a rubber membrane induced by rigid spherical indentor [3]. Valdes, Miquel and Onate tested new methodology for the geometrically non-linear analysis of orthotropic membrane structures with an example in which point load is applied to the prestressed membrane [4]. Milosevic researched the influence of position and intensity of point load on the deflections of membrane structures [5]. Milosevic, Markovic and Stojic investigated the effects of point loads to membrane structures [6].

An ongoing research at Faculty of Civil Engineering and Architecture, University of Nis is aimed at investigating the importance of point load action for membrane structures. The first phase of this research is dedicated to the changes of geometry of membrane structures under point load actions. So far, numerical models have been tested in order to find out which parameters of the load, membrane material and the supports affect the geometry change. In addition, changes of geometry of membrane structures under point loads are compared to the changes of geometry under typical snow load actions. This was done in order to assess the effects of point load action compared to one of the currently dominant actions on membrane structures. Confirmation of the obtained results by testing on real life membrane structures has yet to be done. In the second phase of the research the effects of point load actions on changes of membrane forces will be investigated. This paper presents some of the findings of this research.

2. Point Load Actions

Despite the fact that point load actions are usually neglected in the structural analysis of tensile membrane structures, point loads can act on membranes. Most common point load action is induced by the weight of people standing or walking on the membrane. This is most frequently done during the maintenance, inspection or erection of the structure. Some examples are given in Fig. 1, Fig. 2 and Fig. 3. Other possible causes for point loads on membranes are point connection between layers of the membrane, or point connections between the membrane and the equipment that is sometimes installed under the structure.

There are several aspects that need to be considered when applying point loads on membrane structures. One of the most important aspects is to decide whether the weight of the people should be modeled as a point load or as a concentrated load with small area. The second option represents the load more realistically if the application area of the load is similar to the area of a human foot. However, due to the flexibility of the membrane material, modeling the weight of a human as a point load will produce bigger changes of geometry on the membrane structure. That is why modeling of the weight of the human as a point load in the structural analysis is a safe-sided approach concerning deflections.

The second issue is to decide whether both feet of the human that is on the membrane should be modeled separately, or as one point load. Possible distance between the feet is up to about a meter. The intensities of the two loads representing the feet can be different, however, their sum should be the same, and equal to the weight of the human. The flexibility of the membrane, once again, plays an important role and determines that the biggest changes in geometry are produced when the whole weight of the human is modeled as one point load. Dividing the weight into two point loads with any combination of distance and intensity reduces the deformations of the membrane. Therefore, modeling the weight of the worker in the structural analysis as a single point load is the safe-sided approach with regard to membrane deflections. It is expected that the same conclusion will be valid with regard to changes of membrane forces, since these two are closely connected.

Figure 1. Workers standing on the membrane structure

Figure 2. Cleaning of the membrane structure

Figure 3. Walking on the membrane structure

The third aspect to take into consideration when applying point loads is whether to model them as static or dynamic actions. A human that is standing on the membrane is obviously modeled more accurately as a static point load action, but workers are also often walking on the membrane. Walk is undoubtedly a dynamic action; however, walk on the membrane differs from the walk on the ground. Membranes are curved and this makes the walk more difficult, they are at a certain height which may cause discomfort, and finally they have large deflections which are not common for the usual walking surfaces. All of these facts make the walk slower, which significantly reduces the dynamic component of this action. Therefore, even walk can be approximately modeled as a series of static point load actions. Detailed analysis between the effects of static and dynamic point load actions on membrane structures is not a part of this research.

3. Eurocode for the Structural Design of Tensile Membrane Structures

Joint Research Centre Science and Policy Report: Prospect for European Guidance for the Structural Design of Tensile Membrane Structures, Support to the Implementation, Harmonization and Further Development of the Eurocodes [2] is one of the steps in the development of Eurocode for the Structural Design of Tensile Membrane Structures. The next step is the transformation of this report to CEN Technical Specification (CEN TS) by a Project Team of CEN/TC 250/WG 5 in collaboration with the national mirror committees. After that, the Technical Specification will be converted into Eurocode which is planned to come into force after 2024. This Eurocode will regulate and standardize the structural design of tensile membrane structures in Europe.

One of the most important changes Eurocode for Membrane Structures will bring is the structural design according to the limit state verification. Since the structural design of membrane structures was not codified in many countries, engineers did not have strict instructions on how to conduct the structural analysis. Many of them used the allowable stresses concept that is abandoned in design of other structural materials. In European Design Guide for Tensile Surface Structures [1] this is also discussed. The use of allowable stresses concept for membranes makes the structural design more difficult, since the supporting structure, which is usually made out of steel, has to be verified using the limit state concept. Once the membranes start getting designed according to limit state concept, the structural analysis will become simpler and will cover all structural elements in the same way.

Introduction of limit state design for membranes will also allow for connection between Eurocode for membranes and the other Eurocodes. This means that actions on membrane structures will be taken according to Eurocode 1 [7] in the structural analysis. One of the actions from this standard is also the point load action. In EN 1991-1-1:2002 6.3.4 imposed loads on roofs are defined. For roofs categorized as “roofs not accessible except for normal maintenance and repair” values of actions are given. Therefore, it can be expected that the same action will be used in the structural analysis of membrane structures. Minimum characteristic value for concentrated load may be selected within the range 0,9 to 1,5 kN. The recommended value is 1,0 kN.

4. Research

Based on the presented facts that point loads do act on the membrane structure and that the Eurocode for membranes will be connected to the Eurocode 1, it can be expected that in future point load actions will become a part of the structural analysis of tensile membrane structures. This motivated a research on the effects of point load actions on the membrane structures. The goal of this research was to find out if these effects really are negligible, or is this just a wrong belief which led to neglecting of point load actions in the structural analysis of membrane structures.

4.1. Research description

The research was conducted as a parametric analysis in the software Sofistik 2016 [8]. This software was selected as the most suitable and was previously used in researches of membrane structures, for example by Tanev [9]. Nine parameters were selected for analysis, and these are:

- Position of the point load
- Intensity of the point load
- Intensity of membrane prestress forces
- Tensile modulus of the membrane
- Poisson's ratio of the membrane
- Shear modulus of the membrane
- Patterning direction
- Flexibility of membrane edges
- Geometry of the supports

Numerical models were created in the software and loaded with point load. Values of these parameters were varied and the changes of geometry of the membrane structures under point loads were recorded. By comparing these results it was possible to draw conclusions about the significance of all of these parameters for the deflections of the membrane.

Position of the point load is not defined in the Eurocode 1, so it is up to the engineers to find out which is the least favorable position of the point load. The position of the point load is varied in this research in order to find out which position produces the biggest effects on the membrane structure. Recommended minimum characteristic point load value is given in the Eurocode 1, and the designer of the structure should assess the expected point load value for the specific structure. The point load value was varied so that the relation between it and the effects of this action can be analyzed. Intensity of membrane prestress forces is important during the form finding of the membrane. Here, the intensity was varied in order to find out how it affects the deflections of the membrane under point load. Tensile modulus is one of the most important properties of membrane material. Non-linear membrane behavior is usually in the design practice simplified to orthotropic linear-elastic plane stress relationship [10]. The importance of tensile modulus, Poisson's ratio and shear modulus of the membrane material under point load action was previously unknown and is investigated in this research. There are only a few most commonly used ways of patterning of membranes. Patterning of the membrane depends on the shape of the structure and plays an important role in defining the visual impression about the structure. It is known that deflections under area loads are dependent on the patterning direction [11], but its role under point load actions was not previously analyzed. Influence of the patterning direction to membrane deflections is investigated in this research. Two most frequently used types of membrane edges are rigid and cable edges. One of the aims of this research was to find out if the type of membrane edges is important for changes of geometry under point loads. Finally, geometry of the membrane supports primarily defines the shape of the structure, and was proven to have big impact on deflections under area loads. In this research different support geometries were analyzed in order to find out whether this parameter also has high importance for deflections under point loads.

In addition to investigating how changes of values of analyzed parameters affect the deflections of the membrane under point load, importance of the effects of point load actions on membranes was researched. Comparison of the effects under point load and under snow load was selected as the best way to get to a conclusion. Snow loads and wind loads are dominant actions in the structural analysis of membrane structures, but wind load has a more complex nature, so the snow load was selected as a reference load for comparison. Typical value of 0,6 kN/m^2 was selected for the snow load, and recommended value of 1 kN for point load.

4.2. Research Results

The results of this research are too extensive to be fully presented in this paper. They will be presented in more detail in a doctoral thesis that will be published at the Faculty of Civil Engineering and Architecture, University of Nis. In this paper only some of the main findings will be given.

The basic numerical model that was analyzed in this research is a saddle shaped membrane with a 6×6 m base and the height of 1,5 m. The edges are modeled as fixed. The membrane is prestressed with 3 kN/m in both principal directions and has tensile modulus of 600 kN/m in both principal directions and shear modulus of 25 kN/m in both principal directions, with Poisson's ratio of 0,3. Membrane thickness is 1 mm. Patterning direction is from one high corner to the other high corner of the model. This model is given in Fig. 4. The basic model was loaded with 1 kN point load in the center of the membrane. The deflections of the membrane under this load are given in Fig. 5. Membrane forces under the applied point load for warp and weft are given in Fig. 6. During the course of research, this model was altered in numerous ways, in order to investigate the effects of point load actions.

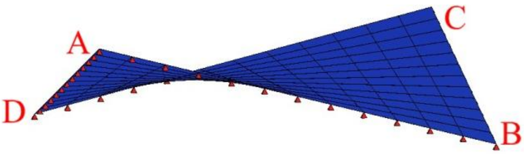

Figure 4. Analyzed model

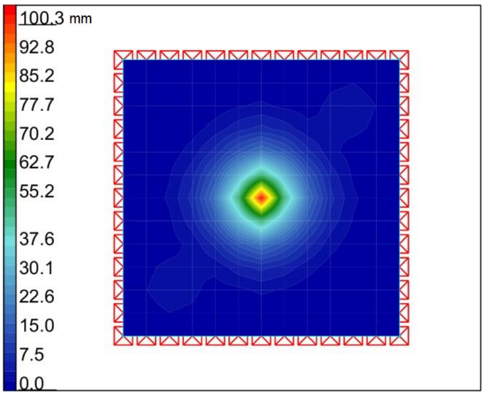

Figure 5. Deflections under 1 kN point load positioned in the center

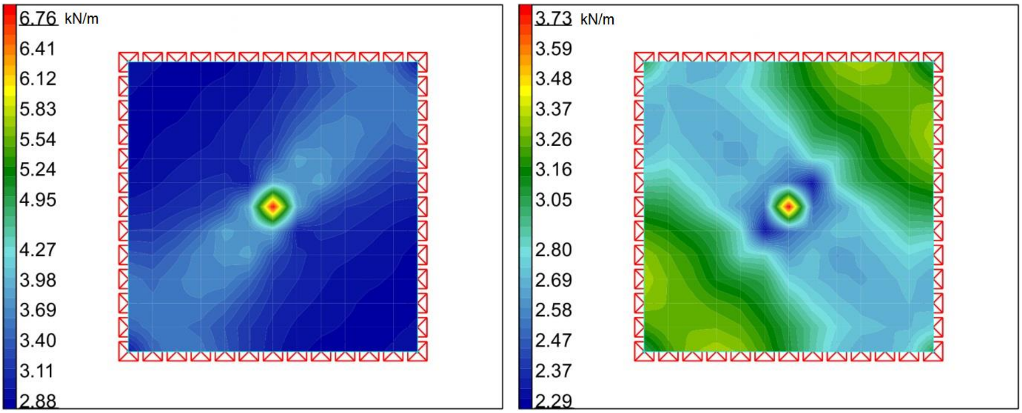

Figure 6. Membrane forces in warp (left) and weft (right) under 1 kN point load in the center

Research results showed how changes of values of each of the analyzed parameters affect the changes of geometry of membrane under point load. The influences of the parameters on membrane deflections under point loads can generally be described as similar to those under area loads, although they do have some specificities. The relations between the parameters and the deflections are mostly non-linear. The increase of parameters' values usually leads to the decrease of changes of geometry under point load. The results also enabled the classification of parameters based on their influence on changes of geometry under point load. Considering all analyzed models, the most changes of geometry, in average, are induced by changes of three parameters. These are: the position of the point load, the intensity of membrane prestress forces and the tensile modulus of the membrane material. This means that in cases when deflections under point loads need to be reduced, change of values of these three parameters would be the most efficient method. Some of the results are presented in Fig. 7. Changing the value of the Poisson's ratio has negligible effects on geometry changes under point loads. These conclusions are valid for the analyzed range of values of the parameters.

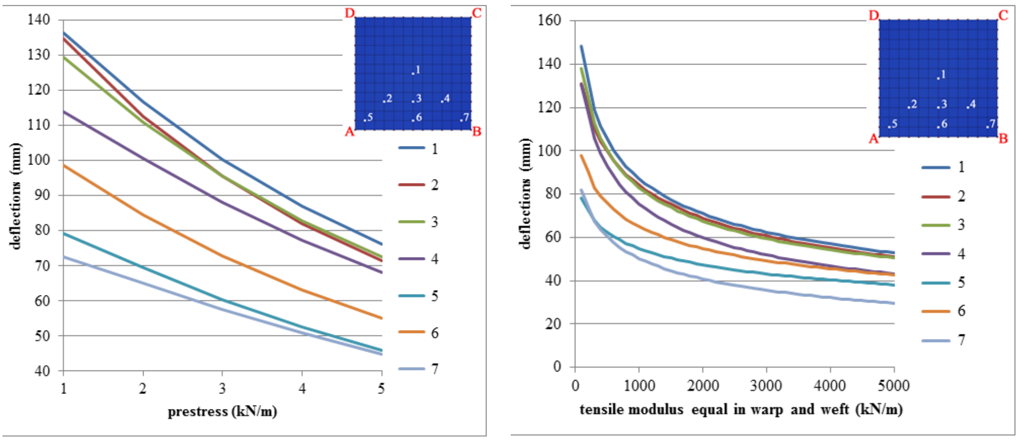

Figure 7. Relation between membrane deflections, 7 different positions of the point load and membrane prestress (left) or tensile modulus (right)

The comparison between deflections under point loads and under snow loads produced some surprising results. Previous research [6] showed that membrane deflections under point load can be almost as big as the ones under area load, which was also unexpected. However, results of this research showed that under certain combinations of analyzed parameters deflections under point load can be larger than deflections under snow load on the same structure. In addition, the number of these combinations was unexpectedly high. Since the current design practice is to conduct the structural analysis without point load actions, it can be concluded that such structures may be seriously threatened by point loads. There are no strict limits on maximum deflections of membrane structures. However, the clash between the membrane and other surfaces must be avoided. If point load actions were not considered in the analysis, and it is now proven that they can produce larger deflections, than that structure might not be completely safe. This finding can have complex consequences. One of the most important ones is the obligatory incorporation of point load actions into the structural analysis of membrane structures. Further researches need to be undertaken in order for this to happen. The effects of point loads to changes of membrane forces still have to be investigated.

5. Conclusion

This paper shows how current literature about membrane structures mostly neglects the point load actions. With the creation of Eurocode for the Structural Design of Tensile Membrane Structures and its future connection to Eurocode 1, it is expected that point load actions will be included in the structural analysis of membrane structures. This motivated a research about the effects of point loads on membrane structures. The findings of this research were unexpected and show that these effects can be much larger than previously believed. Obtained results justify the intention to incorporate point load actions into the structural analysis of tensile membrane structures. Based on this, it is concluded that further research about the influence of point loads on membrane structures should be conducted.

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