ROUND ROBIN Exercise 4

Reliability analysis of a simple membrane structure: a hyperbolic paraboloid

This Round Robin Exercise 4 is launched by the TensiNet Working Group Specifications and WG5 of the COST Action TU1303 Novel Structural skins and aims at collating reliability indexes for a basic tensioned hypar structure.

Link: *http://www.tensinet.com/files/Announcement___calls/Round%20Robin%20exercise%20IV%20-%20call%20-%2030112017.pdf*

The exercise is started by Ir.-Arch. Elien De Smedt, Prof. Marijke Mollaert, Prof. Lincy Pyl, Prof. Peter Gosling, Dr.-Ing. Jörg Uhlemann and Prof. Jean-Christophe Thomas. Research institutes, universities, specialised laboratories and engineering offices are invited to volunteer to the Round Robin exercise 4.
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1 What is a "round robin"?

A **"round robin"** exercise refers to an activity (e.g. measurement of properties, structural analysis, or physical experiment) performed independently by different groups, institutions, or companies. Each participant will provide an independent solution to a particular problem. Once the exercise is completed the solutions are reviewed and analysed. The collective outcomes are then used to produce a number of key conclusions and recommendations.

2 Antecedents launched by the TensiNet Working Groups

Round Robin Exercise 1 (**paper**), launched by the TensiNet Working Group Materials & Analysis, was a comparative study of analysis methods and results for a set of well-defined membrane structures. The results were published in 'Engineering Structures'. (available at *http://eprint.ncl.ac.uk/pub_details2.aspx?pub_id=184881*)

Round Robin Exercise 2 (**call**), launched by the TensiNet Working Group Materials & Analysis of the COST Action TU1303 Novel Structural skins. A comparative exercise was carried out by practitioners and Universities worldwide on the interpretation of biaxial and shear test data, i.e. the assessment of the stiffness of architectural fabrics and how these properties are represented in the analysis of a structure.
(available at *http://www.tensinet.com/files/Announcement___calls/NEW_CALL_ROUND_ROBIN_II_-1.pdf)*

Round Robin Exercise 3 (**paper**), launched by the TensiNet Working Group From Material to Structure and Limit States: Codes and Standardisation of the COST Action TU1303 Novel Structural Skins, collated wind tunnel and CFD (Computational Fluid Dynamics) data for the basic shapes of tensioned surface structures. The wind loading on basic membrane shapes was assessed and the outcomes were related to the structural analysis of a membrane structure.
(available at *http://www.sciencedirect.com/science/article/pii/S1877705816321579*)

Round Robin Exercise 4 (call), launched by the TensiNet Working Group *Specifications and Eurocode* and the Working Group 5 of the COST Action TU1303 Novel Structural Skins *From Material to Structure and Limit States*, is set up to evaluate the different methods used to obtain the reliability index and to collate the different reliability indexes for a simple tensioned hypar structure.

3 The purpose of the round robin exercises

Firstly, and most importantly, it should be noted that the round robin exercise is *not a competition*. The exercise aims to determine the current state of activity in a particular field and to assist in the development of that field.

Membrane structures are used for temporary events (e.g. festivals), but also for permanent use (e.g. stadiums). These structures can be built at any scale and can be used for many functions. Though they are subjected to the same environmental loads as traditional buildings, they do not yet have a standardised building code (the Eurocode) such as exists for traditional buildings (EN 1990 – EN 1999). Contemporary calculation methods to design membrane structures are still expert judgement based.

Currently, CEN/TC 250 WG5 Membrane Structures, is writing the different parts of the Technical Specification in order to eventually have a Eurocode for Membrane Structures.

The design of traditional structures according to the Eurocode is based on a partial factor method, with the partial factors based on statistical data. There is a lack of statistical information concerning membrane material properties because the results of the tests done in the different firms are kept confidential. Moreover, because of the large variability of membrane materials it would be difficult to establish a partial factor value covering all membrane materials.

A structure designed according to the Eurocodes needs to fulfil specific criteria. One of the criteria is that the reliability index of the structure, considering a consequence class of 2 and a 50-year design period, is not lower than 3.8. The reliability index can be calculated by various methods, using different approaches (Monte Carlo, Latin Hypercube Sampling, etc.).

This round robin exercise is established to get more insight in the calculation methods to obtain the reliability index and to evaluate the difference between the obtained results.

The exercise will be performed for a simple hyperbolic paraboloid membrane structure (called hypar), see paragraph 5. for description.

Within this perspective, **Round Robin Exercise 4 is launched to explore and evaluate the different methods used to obtain the reliability index for a simple tensioned hypar structure.**

4 Principles

The Round Robin exercise is proposed as a non-commercial activity. It is intended to serve the purpose of advancing scientific knowledge and engineering practice in the analysis and design of membrane structures. Participation in the Round Robin exercise is further based on the following principles:

- Involvement in the round robin exercise is voluntary,
- Completion of the round robin tasks is undertaken without fee and liability,
- The completed tasks will not be used outside the remit of the round robin exercise and will not be made available in a format that could be used for design purposes by a third party,
- The round robin outputs will be reported anonymous and the participants will be acknowledged in all dissemination (journal papers, reports etc.), while the ownership of the data will remain with the participants.

5 Description case study

The structure is tensioned between two high and two low points (Figure 1 and Figure 2). The boundaries are reinforced by means of a cable. The structure is designed under the specified load cases, the dimensions and the prestress are given in Table 1.

Length	6	m
Width	6	m
Height	2	m
Cable diameter	12	mm
Prestress warp	**4**	kN/m
Prestress fill	**4**	kN/m
Cable force	30	kN

Table 1: Dimensions and prestress of the hypar

The material properties are given in Table 2.

Elasticity modulus warp *t	600	kN/m
Elasticity modulus fill *t	600	kN/m
Shear modulus *t	30	kN/m
Poisson coefficient	0.4	/
Elasticity modulus cable	205	kN/mm²
Material strength warp	97	kN/m
Material strength fill	87	kN/m

Table 2: Considered material properties

The hypar will be subjected to three load cases (combinations without coefficients):

- load case 1: pre-stress,
- load case 2: pre-stress + snow and
- load case 3: pre-stress + wind uplift.

Of which:

Snow	0.6	kN/m²
Wind uplift	-1.0	kN/m²

Table 3: Considered snow and wind load

The reliability index will be calculated for each load case separately.

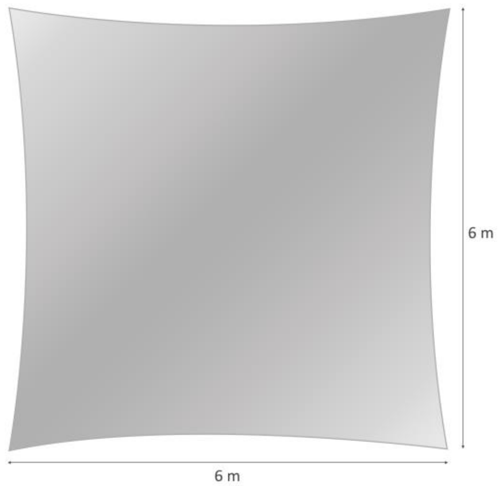

Figure 1: Hypar, top view

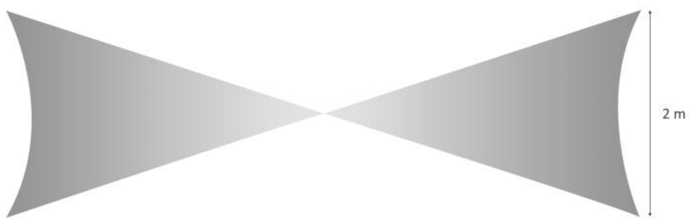

Figure 2: Hypar, side view

6 The considered variables and stochastic characteristics

The considered variables are:

- prestress in warp direction (P_{warp}),
- prestress in fill direction (P_{fill}),
- stiffness in warp direction (Et_{warp}),
- stiffness in fill direction (Et_{fill}),
- shear modulus (G),
- Poisson coefficient (v) (?),
- material strength in warp direction (f_{warp}),
- material strength in fill direction (f_{fill}),
- snow load (Q_s) and
- wind load uplift (uplift, Q_w).

The overview of the stochastic characteristics per variable is given in Table 4 and Table 5. The values were discussed during the Working Group 5 meeting (Cost Action TU1303) in Brussels (17/10/2017), the value of the COV for the prestress is based on expert advice.

Variable	Distribution	Mean value (μ)	Standard deviation (σ)	Coefficient of Variation (COV) *	Unit
$\boldsymbol{P_{warp}}$	normal	**4**	0.75	0.25	kN/m
$\boldsymbol{P_{fill}}$	normal	**4**	0.75	0.25	kN/m
$\boldsymbol{Et_{warp}}$	normal	600	40	0.07	kN/m
$\boldsymbol{Et_{fill}}$	normal	600	40	0.07	kN/m
$\boldsymbol{G}$	normal	30	3	0.10	kN/m
$\boldsymbol{f_{warp}}$	normal	97	4.3	0.044	kN/m
$\boldsymbol{f_{fill}}$	normal	87	3.6	0.041	kN/m

Table 4: Stochastic characteristics per variable (Gosling, et al., 2013) (Uhlemann & Stranghöner, 2017)

Variable	Distribution	Nominal value	Mean value (μ)	Standard deviation (σ)	Coefficient of Variation (COV) *	Shape factor (α)	Mode (u)	Unit
$\boldsymbol{Q_s}$**	Gumbel	0.6	0.66	0.198	0.30	6.48	0.57	kN/m²
$\boldsymbol{Q_w}$**	Gumbel	-1	-0.7	-0.245	0.35	-5.24	-0.59	kN/m²

Table 5: Stochastic characteristics of the considered snow and wind load (Holicky & Sykora, 2010)

*Calculation of the Coefficient of Variation

$$COV = \frac{\sigma}{\mu}$$

**Due to the fact that snow and wind are described by a Gumbel distribution, two extra entities are needed: the shape factor and the mode. The calculation of the mean value, shape factor and mode of the wind and snow load are given below.

- Mean value, snow: $\mu_Q = 1.1\ x\ X_k$
- Mean value, wind: $\mu_Q = 0.7\ x\ X_k$
- Standard deviation: $\sigma_Q = CoV \mu_Q$
- Shape factor: $\alpha = \frac{\pi}{\sigma\sqrt{6}}$
- Mode: $u = \mu_Q - \frac{\Upsilon}{\alpha}$
- Euler constant: $\Upsilon = 0.58$

7 Reporting of results

To be able to collate the different calculation reports and results for the reliability index of the tensioned hypar structure, a summary description of the used method should be made available.

The reliability index should be calculated based on an appropriate stress value in the membrane after each load case (1, 2, 3) is applied. A representative stress drawing, showing the peak values of the stress in the membrane as well as the realistic high value to be considered, should be provided (as shown in Figure 3). The stress view should be taken from the dimensioning file.

For each load case, the reliability index will be given for the warp direction, fill direction and the overall structure (warp + fill).

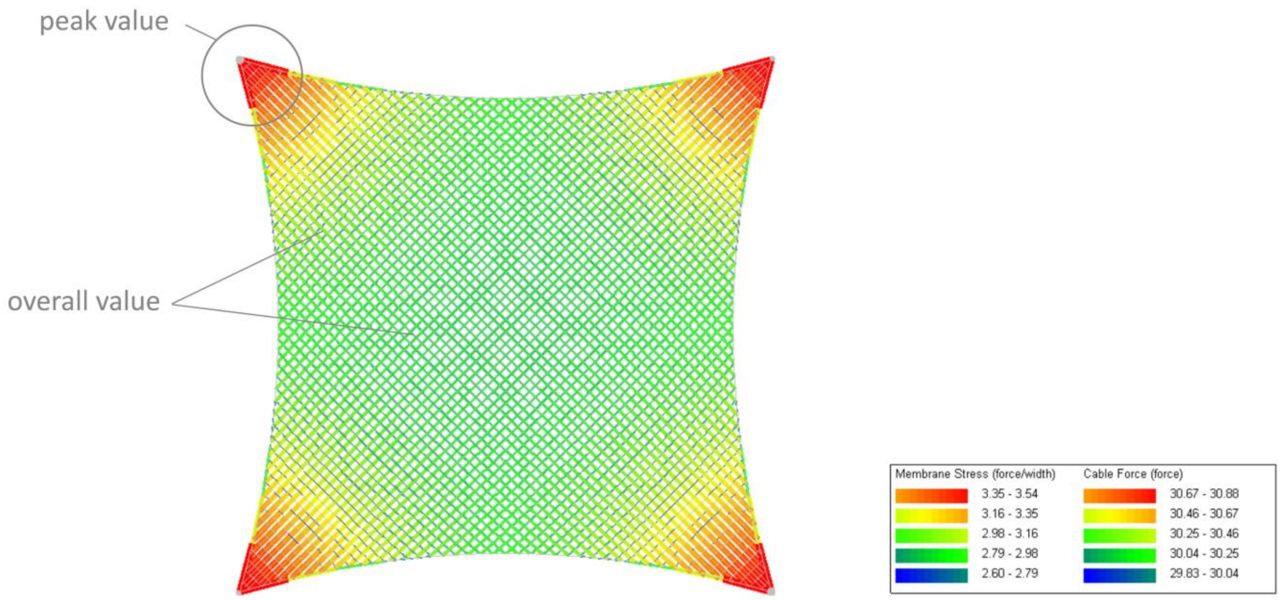

Figure 3: Representative drawing of the distribution of the stress in the membrane and the forces in the boundary cables

8 Timeline

November 2017	**Round Robin 4 is launched.** **Research institutes, universities, specialized laboratories and engineering offices are invited to volunteer to provide the reliability analysis and index for a simple tensioned hypar structure.** Participants are asked to express their interest in the exercise by emailing Ir. Arch. Elien De Smedt at Elien.De.Smedt@vub.be.

9 References

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