17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

SEISMIC RESPONSE OF TENSILE FABRIC STRUCTURES CONSIDERING DIFFERENT SEISMIC SOURCE MECHANISMS

A.D. García-Soto(1), J.G. Valdés-Vázquez(2), A. Hernández-Martínez(3), M. Jaimes(4), J.C. Vielma-Pérez(5)

(1) *Researcher, Department of Civil Engineering, Universidad de Guanajuato, adgarcia@ugto.mx*
(2) *Researcher, Department of Civil Engineering, Universidad de Guanajuato, valdes@ugto.mx*
(3) *Researcher, Department of Civil Engineering, Universidad de Guanajuato, alejandro.hernandez@ugto.mx*
(4) *Researcher (Associate), Institute of Engineering, UNAM, mjaimest@iingen.unam.mx*
(5) *Researcher, Faculty of Engineering, P. Universidad Católica de Valparaíso, juan.vielma@pucv.cl*

Abstract

Tensile fabric structures (TFSs) are very light structures with striking designs, which are very often used in the practice, although not thoroughly studied from the structural engineering perspective. TFSs have been usually investigated for wind loading and it is known that they exhibit highly geometrical non-linear displacements. The response of TFSs subjected to seismic loads is not commonly found in the literature, although it has been reported that they can be sensitive to such dynamic loading, especially with regards to the reactions at the masts and cables.

This study investigates the seismic response of tensile fabric structures (TFSs) under the action of ground motions of different source mechanisms. Ground motions due to intermediate depth intraslab mechanism and due to subduction interface mechanism are used as input to the system (i.e., the TFSs). To obtain the TFSs seismic response, a finite element formulation reported in a previous study, and which accounts for wrinkling phenomena, orthotropic material modeling, and geometrical nonlinearity, is employed for each of the selected accelerograms. The analyses are performed considering *form-finding*, prestressed cables and seismic loading.

Key conclusions:

- The research shows that the seismic response of TFSs should not be disregarded in the design.
- The reactions at the supports can be very high in terms of axial force for records with large PGA, which should be considered in codified design.
- Differences depending on the type of seismic source mechanism are not so significant; it seems that differences are more related to near-source or far-field ground motions.

Keywords: tensile fabric structures; geometric non-linearity; supports reaction; seismic source mechanisms; near-source

1. Introduction

The seismic response of tensile fabric structures (TFSs) has been reported in a previous study [1], where it was reported that, unlike it could be thought, the seismic demand on these of light structures with impressive designs could be important. It was found that, although the stresses in the fabric are very low as compared with the capacity of the membrane, the supporting structures could exhibit a very high increase in the axial forces [1], as in the case of masts and tensors.

Since it has been reported in the literature that different seismic source mechanisms could lead to higher demands on certain structures, depending on their dynamic characteristics [2], it could be important to also inspect the effect of using earthquake records originated from different source mechanisms in the TFSs as input signals to assess the response in these kind of structures. Among the different seismic source mechanisms that contribute to the seismic hazard of a given region, it could be mention the subduction interface [3], the intermediate-depth intraslab [4] and local [5] mechanisms.

The main objective of this study is to assess possible differences in the structural response of TFSs under the action of earthquake-induced ground motions originated from different source mechanisms.

2. Considered TFS and ground motions

2.1 Description of TFS geometry and material properties

A variant of a hyperbolic paraboloid (commonly known as “hypar” in the literature), except that is has a double configuration (thus referred here as “double-hypar”), and shown in Figure 1, is analyzed in this study. In Figure 1 the sub-structure elements in tension are shown in blue, while in yellow the prestressed cables surrounding the TFS are depicted; in pink, inside the perimeter delimited by the prestressed cables of the membrane, which is prestressed as well, the membrane is shown too.

Initially, the prestressed cables are straight; then a procedure known as *form-finding* is performed to obtain the deformed (final) shape; finally, this final shape is used to carry out the seismic analysis.

The prestress force and stress for the form-finding are 2kN/m for the membrane and 20 kN for the cable, respectively. Since the direct stiffness method was employed to find the minimum surface, the material properties are not that relevant at this stage, that’s why small values are used and listed in Table 1.

Table 1. Material properties for the *form-finding*

Membrane tensile stiffness $E_w = E_f$	0.001 kN/m
Membrane Poisson relation	0.4
Membrane thickness	1 mm
Cable elasticity E	0.001 kN/m^2
Cable cross section	7.125e-05 m^2

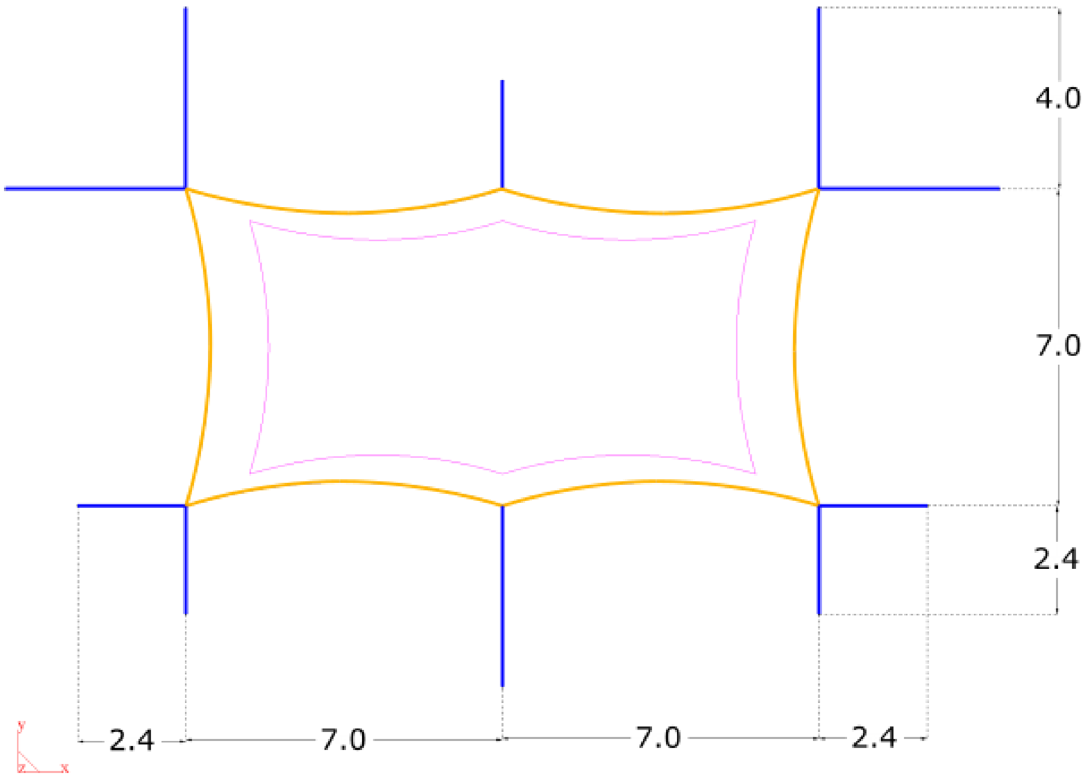

Fig. 1 – Double-hypar plan view. Dimensions in meters

Once the *form-finding* is performed, the structure is analyzed; a 3D depiction of the TFS is showed in Figure 2; the masts are showed in red, which are 5 m and 3m long in alternated fashion; the tensors are shown in blue. For the double-hypar in Figure 2, the material properties for the seismic analysis are listed in Table 2. The prestress forces are kept during the seismic analysis.

Table 2. Material properties for seismic analysis

Membrane tensile stiffness $E_w = E_f$	800 kN/m
Membrane Poisson relation	0.4
Membrane thickness	1 mm
Membrane density	1,800 kg/m^3
Cable elasticity E	210 GPa
Steel Cable cross section	7.125e-05 m^2
Tensor elasticity	210 GPa
Steel Tensor cross section	7.125e-05 m^2
Mast elasticity	210 GPa
Steel Mast cross section	2.187e-03 m^2
Steel density	7,500 kg/m^3

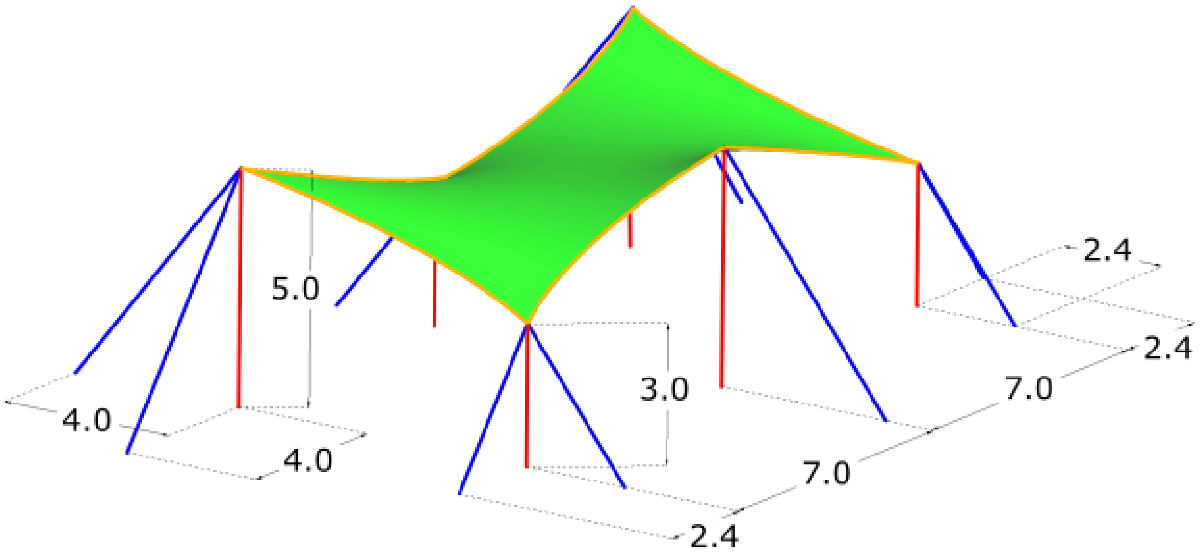

Fig. 2 – Double-hypar 3D view. Dimensions in meters

2.2 Set of ground motion recordings employed

The TFS was subjected to dynamic time-history analyses for earthquakes with two source mechanisms: one is a subduction interface event and the other is an intermediate-depth intraslab event. The recording for the former is shown in Figure 3, while the recording for the later in Figure 4.

To obtain the ground motions from two expected large (design) earthquakes for the considered region, which are associated to design spectra, the following procedure is followed: 1) to estimate the design spectrum for the region under study; 2) from this spectrum and an assessment of the strong ground motion duration, representative of the region, the power density spectral function (PDSF) [6]; 3) use of a representative seed (i.e., a representative seismic record of the region) to compute the PDSF and the design spectrum associated to steps (1) and (2) above, which is to be considered as the mean spectrum design used. Then, if the procedure is repeated for other seed, this results in a set of coupled synthetic simulations related to a target design spectrum, which could be employed to carry out a non-linear structural analysis.

Since the non-lineal response of structures is highly sensitive the ground motion parameters, such as spectral acceleration, frequency content or duration, a careful selection of the records used as seeds is required for the method employed in this study. To adequately describe the structural response of the TFSs, and the possible influence of the frequency content, records originated from two actual seismic events are used: 1) the Mw8.1 subduction interface earthquake of September 19th, 1985, recorded at accelerometric station known as AZIH and, 2) the Mw8.2 intermediate-depth instraslab earthquake of September 7th, 2017, recorded at station known as SCRU. The former is still in the memory of many Mexicans, because of the wide destruction across Mexico City and the large number of deaths it left behind, being the most severe and destructive earthquake ever recorded in modern times; it was originated in the Guerrero and Michoacán coasts, about 300 km far from Mexico City, and occurred in the morning of 19th September 1985 at 7:19:45 (local time), before the elementary schools were full with children (luckily), otherwise (i.e., if it had occurred later) the number of fatalities could have increased substantially, since many elementary schools collapsed. The later, is an intermediate-depth normal-faulting earthquake, also very destructive, but this time the Gulf of Tehunatepec (in Chiapas and Michoacán states, in southeast Mexico) were the places where its devastating effects acted; this is the biggest earthquake in the Pacific Coast of Mexico since the Mw8.2 Jalisco earthquake, which occurred in 1952. The second considered event in this study, did not lead to fatalities in Mexico City; incredibly, just a few days later, a Mw7.1 earthquake occurred in the 19th September (i.e., in the same date as the Mw8.2 1985 event!) leading to many deaths in Mexico City and other states; this event is not considered in the present study, but it could be used in future papers.

Fort the purposes of the present study, synthetic accelerograms from the two earthquakes described above, which are associated to a design spectrum for Zone C for soil type as described in NMX-R-079-SCFI-2015 [7], are showed in Figures 3 and 4.

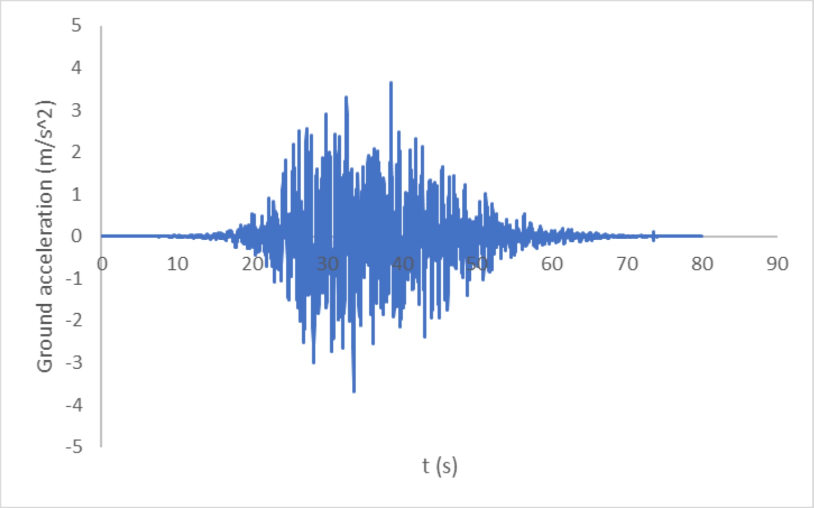

Fig. 3 – Subduction interface earthquake record

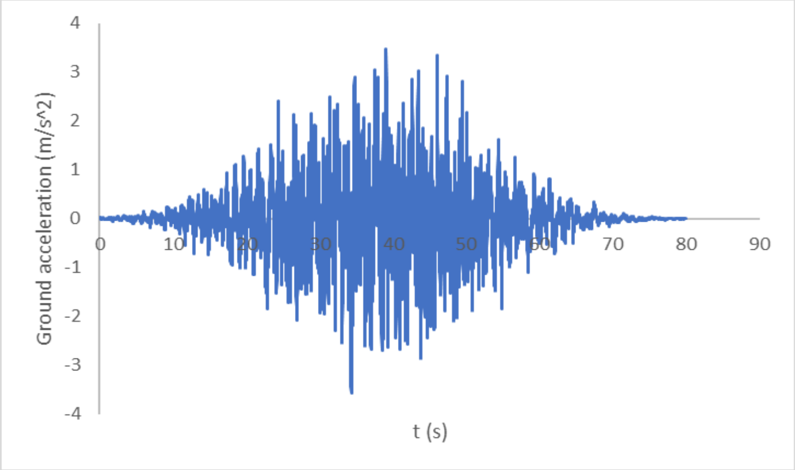

Fig. 4 – Intermediate-depth intraslab earthquake record

3. Results

To compute the non-linear response of the TFS (and report the results) of this study, the finite element method (FEM) is used. The method and background employed are briefly described in the following.

A membrane is a thin shell with no flexural stiffness, in essence; that’s why it is supposed not to resist compressive stresses. Therefore, only the in-plane stress resultants are taken into account. The position of points on the two-dimensional surface in the Euclidean space provides the deformation state for a membrane.

Some membrane structures have a very low flexural stiffness that can support a small amount of compressive stress before buckling. Thus, membranes are pre-stressed; in this way compression is avoided.

For the membrane theory, a curvilinear coordinate system based on differential geometry of surfaces is to be employed, in which Greek indices on membrane mid-surface take on values of 1 and 2 in a plane stress state in the Euclidean space. The components for the membrane surface (plane stress state) are obtained as

$$E_{\alpha\beta} = \frac{1}{2}\left(g_{\alpha\beta} - G_{\alpha\beta}\right) \tag{1}$$

If appropriate constitutive equation to relate the second Piola-Kirchhoff stress tensor and the Green-Lagrange strain tensor in curvilinear coordinates is used, the components of the stress tensor are

$$\boldsymbol{S} = S^{\alpha\beta}\left(\boldsymbol{G}_{\alpha} \otimes \boldsymbol{G}_{\beta}\right) \tag{2}$$

Once the tensor is determined, the virtual internal work can be expressed in curvilinear coordinates as

$$\delta W^{int} = \int_{V} \delta E_{\alpha\beta} S^{\alpha\beta} \, dV \tag{3}$$

The complete virtual work formulation is expressed in a matrix form, and because only implicit schemes are solved for structural dynamic problems, the semi-discrete equations of motion to be solved are

$$\boldsymbol{f}^{int}\left(\boldsymbol{u}_{n+1}\right) + \boldsymbol{M}\ddot{\boldsymbol{u}}_{n+1} = \boldsymbol{f}^{ext}\left(\boldsymbol{u}_{n+1}\right) \tag{4}$$

where the acceleration vector $\ddot{\boldsymbol{u}}_{n+1}$ must be integrated in time steps to solve the algebraic equations for $\boldsymbol{u}_{n+1}$ from the second-order differential equations. The interested reader is referred to [8] for further details.

Using the above-describe concepts, the seismic axial forces as a function of time in one of the masts (3m long) of the TFS in Figure 2 are computed and shown in Figure 5; the results for the subduction interface record from Figure 4 are shown in blue, while the results for the instraslab event of Figure 3 are shown in orange. Results for a 5m long mast are similar and not shown for brevity.

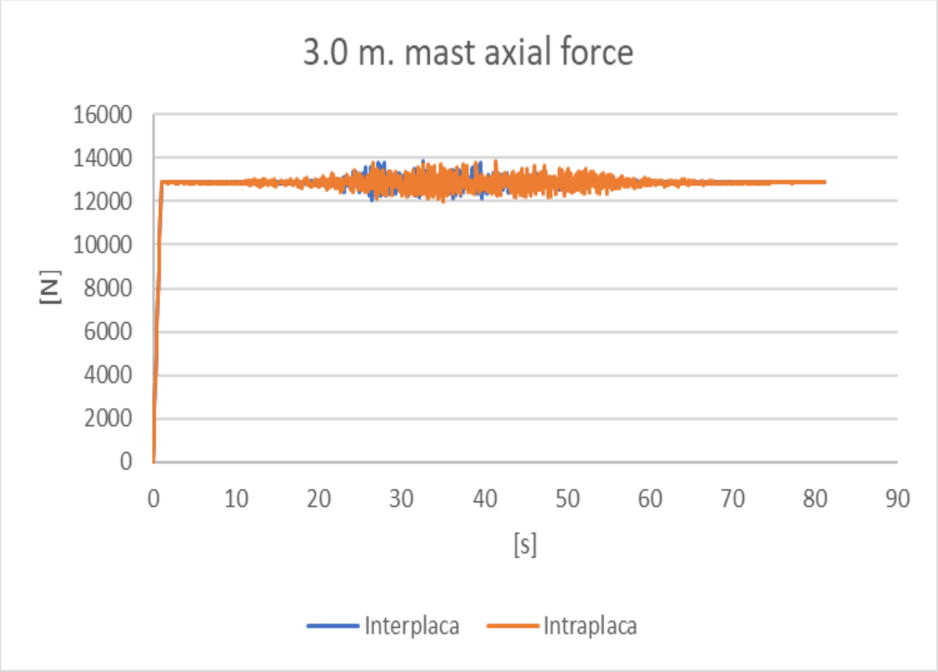

Fig. 5 – Seismic axial forces in a 3m long mast of the TFS

Results for the tensile forces in a long tensor, the cable maximum stresses, and the membrane maximum displacements and stresses are shown in Figures 6, 7, 8 and 9, in which the format used in Figure 5 is also employed.

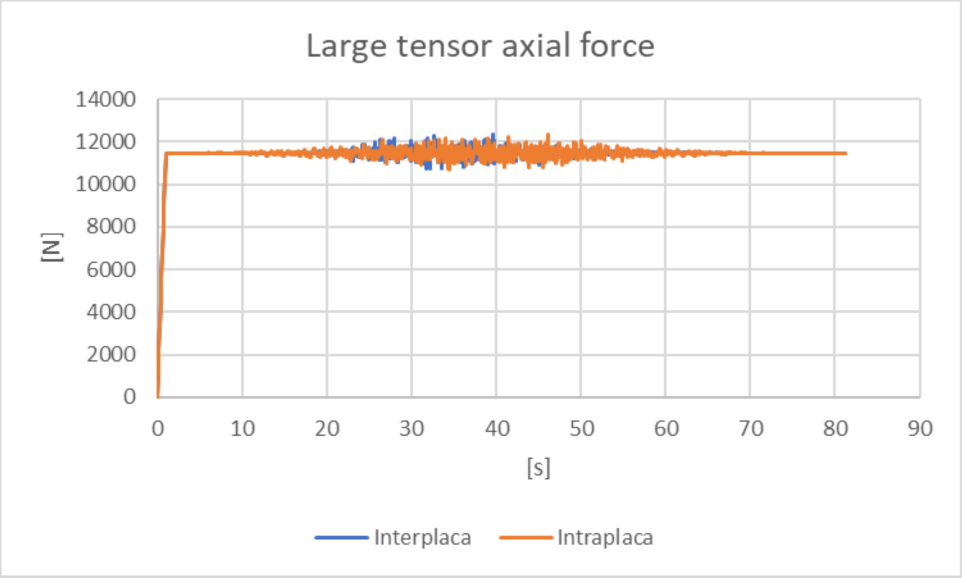

Fig. 6 – Seismic axial forces in a long tensor

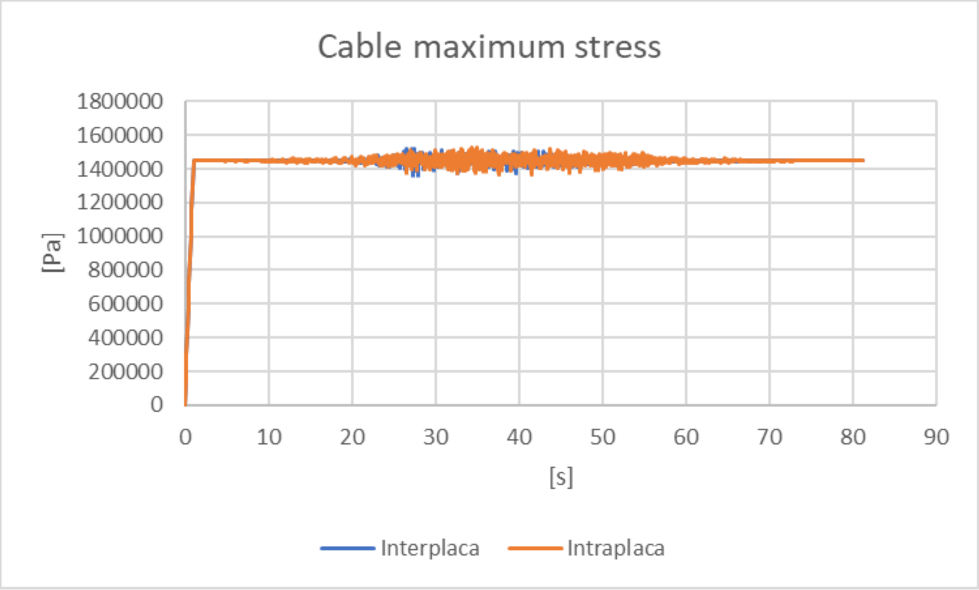

Fig. 7 – Cable maximum stresses

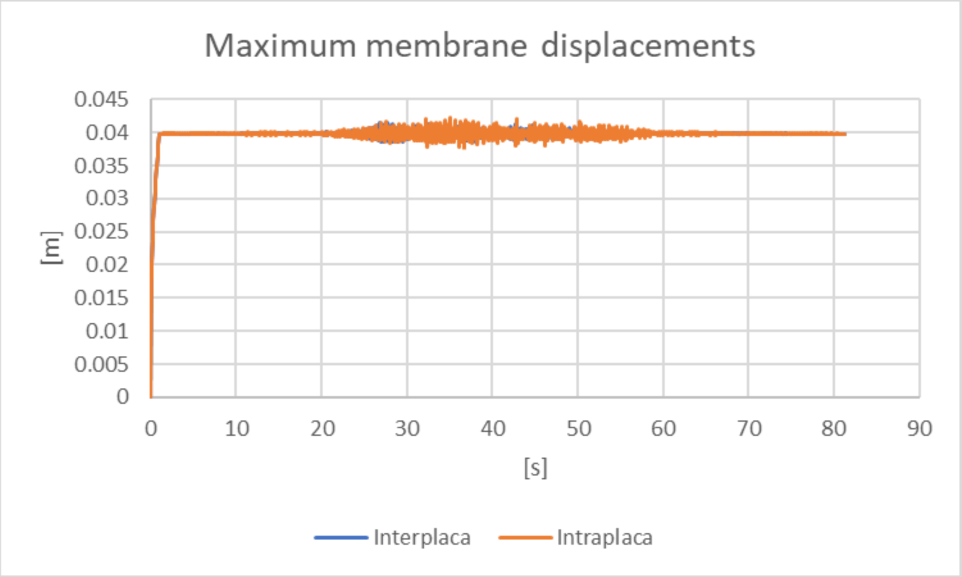

Fig. 8 – Membrane maximum displacements

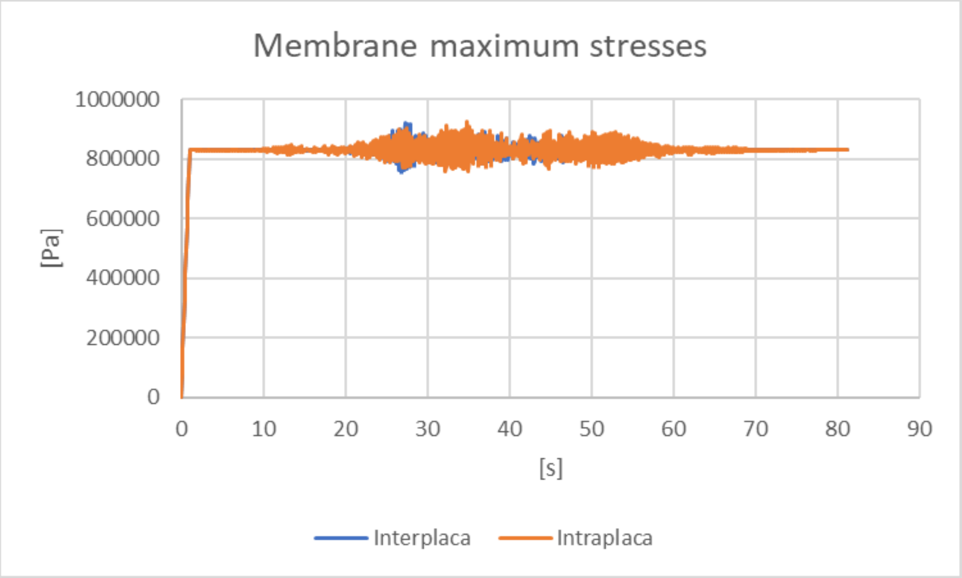

Fig. 9 – Membrane maximum stresses

Results from Figures 5-9 indicate that the seismic response of the double-hypar is nor very significant, neither for the subduction interface earthquake, nor for the intermediate-depth intraslab one. This is contrasting with the results found in [1] for the single hypar. Rather than attributing this to the geometric differences, the reason is than in [1] an Italian record with near double peak ground acceleration (if compared with records in Figures 3 and 4) was used. The Italian accelerogram was recorded in Norcia, in Forca Canapine Station on October the 30th, 2016 and was originated from a Mw6.6 earthquake, possibly a near-site event, since the peak ground acceleration is very large. For comparison purposes, the double-hypar is also subjected to the Norcia, Italy recording, and the results for axial force at the short mast are plotted in Figure 10 (in grey), together with those generated by using the Mexican earthquakes.

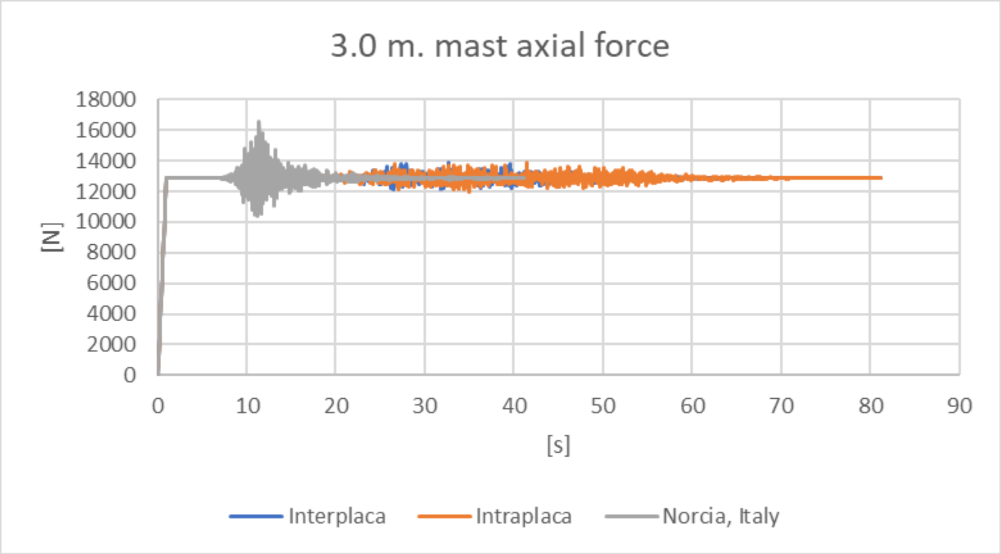

Fig. 10 – Sesimic axial forces in a 3 m long masts using the Italian and Mexican recordings

Results in Figure 10 indicate that the Norcia, Italy recoding does indeed lead to significant increases of the seismic axial forces with the corresponding implications for design [1]. From the overall results described in this article, is concluded that rather than the source mechanism, it is the consideration of near-source versus far-field ground motions the aspect which is critical for design. Therefore, the seismic design of TFSs in near-source sites should not be disregarded and incorporated in codified design. Although not significant earthquake-induced demands were observed for both types of Mexican earthquakes, future research is recommended to cover other aspects, including the distance from the epicenter to the site where the TFSs could be located.

4. Conclusions

The non-linear seismic response of a TFS (a double-hypar) subjected to synthetic recordings from subduction interface and intermediate-depth Mexican earthquakes, as well as from an Italian earthquake with large peak ground acceleration, was carried out by using a membrane FEM formulation. For the considered records, it is concluded that not the source mechanism, but possibly the distance from the epicenter to the site where the TFS is located, is the critical aspect for design purposes. Nevertheless, future research is recommended to thoroughly investigate this finding. Since previous studies for a single hypar, and the present study for the double-hypar proves that significant axial forces can be induced in the supporting elements of TFSs due to earthquakes, the seismic design of membrane structures should not be disregarded by designers.

5. Acknowledgements

The support from Universidad de Guanajuato is gratefully acknowledged.

6. References

[1] Valdes-Vazquez JG, García-Soto AD, Hernández-Martínez A (2019): Dynamic analysis of hypar membrane structures subjected to seismic excitations, *Rev. int. métodos numér. cálc. diseño ing.*, **35** (1), 1-11.

[2] García-Soto AD, Pozos-Estrada A, Hong HP, Gómez-Martínez R (2012): Estimación del peligro sísmico debido a sismos interplaca e inslab y sus implicaciones en el diseño sísmico. *Revista de Ingeniería Sísmica*, 86, 27-54 (in Spanish).

[3] García-Soto AD, Jaimes MA (2017): Ground-motion prediction model for vertical response spectra from Mexican interplate earthquakes, *Bulletin of Seismological Society of America*, 107, 887–900.

[4] Jaimes MA, García-Soto AD (2020): Updated ground-motion prediction model for Mexican intermediate-depth intraslab earthquakes including V/H ratios, *Earthquake Spectra* (accepted; in press).

[5] Jaimes MA, Lermo J, García-Soto AD (2016): Ground-Motion Prediction Model from Local Earthquakes of the Mexico Basin at the Hill Zone of Mexico City, *Bulletin of the Seismological Society of America*, 106 (6): 2532–2544.

[6] Der Kiureghian A, Neuenhofer A (1992): Response spectrum method for multi-support seismic excitation, *Earthquake Engineering and Structural Dynamics*, 21, 713-740.

[7] NMX-R-079-SCFI-2015 (2015) Norma Mexicana Escuelas – Seguridad estructural de la infraestructura física educativa – requisitos. Secretaría de Economía (in Spanish).

[8] Valdés-Vázquez JG, Miquel J, Oñate E (2009): Nonlinear finite element analysis of orthotropic and prestressed membrane structures, *Finite elements in Analysis and Design*, Germany, vol. 45, 395-405.