THE EFFECT OF GEOMETRIC IMPERFECTIONS ON THE BUCKLING RESPONSE OF A THIN MASONRY SHELL STRUCTURE SUBJECTED TO EARTHQUAKE LOADS

Eftychia DICHIROU¹, Matthew J. DEJONG²,

ABSTRACT

The presence of initial geometric imperfections in thin masonry shell structures might be particularly important in an earthquake, as they can cause reductions to their load-carrying capacity. This paper aims to assess the effect of geometric imperfections on the seismic capacity and buckling load of an 8mx10m unreinforced, thin masonry shell structure. The structure has the same geometry as the Droneport Prototype that was constructed as part of the Venice Architecture Biennale 2016. An elastic buckling analysis is performed on the design shell geometry using finite element modelling. Repeated simulations are conducted to investigate the sensitivity of buckling to reductions in shell thickness. These analyses include the presence of initial shape and thickness imperfections which are likely to arise in the construction stage. To quantify the initial imperfection parameters, the actual shell geometry of the Droneport Prototype was surveyed using a laser scanner. The sensitivity of buckling to initial geometric imperfections is examined by performing analyses on multiple imperfection patterns that are generated from a tool which is based on the random field theory and uses the laser scan data as input. Comparison of the results enables determination of the extent to which imperfections influence the seismic collapse of thin masonry shells, including identification of the extreme thinness limits at which seismic buckling becomes an issue. The inclusion of a realistic representation of the imperfections that might occur in the construction of a shell structure during the design process is novel and important, to ensure seismic safety, making the design of thin masonry shells more robust in moderate earthquake-prone regions.

Keywords: Masonry shells; Earthquake design; Geometric imperfections; Laser scanning; Buckling analysis

1. INTRODUCTION

Tile vaulting is a centuries-old construction technique which has recently revived interest due to the development of powerful form-finding tools for the analysis and design of masonry structures (Davis et al., 2012). These innovative computational tools that are based on interactive three-dimensional equilibrium methods, enabled traditional tile vaulting to become a flexible and versatile technique through which, the expressive free-forms of modern architecture could be made possible (López et al., 2016). The contemporary tile vaulting has become particularly attractive for the developing world, as it can also provide a sustainable design alternative. The ability of tile vaulted systems to effectively support their own weight through their optimized form, while using sustainable earth-based materials such as soil-pressed tiles, their extreme thinness which reduces the volume of material required for their construction, and the self-supportive nature of masonry which reduces the need of excessive formwork, are the main parameters which contribute towards the achievement of significant financial and environmental benefits (Ramage et al., 2010). However, the use of minimal formwork for the construction of thin masonry shells can lead to the unavoidable generation of geometric imperfections. Several studies have shown that the presence of initial geometric imperfections on shell structures can cause reductions to their load-carrying capacity (Chen et al., 2016), making their effect in an event of an earthquake to be particularly important. Accounting for the initial geometric imperfections that may occur in the construction of a shell structure during the design process, is therefore vital for ensuring a

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safe seismic design. Initial imperfections are variable in nature and hence, providing a realistic representation of initial imperfections in the design stage, still remains a major challenge for engineers. The traditional approach to the modelling of initial imperfections, which involves the consideration of a specific imperfection shape is, in many cases inadequate for predicting the real geometry of the structure (Schenk & Schuëller, 2003). In such an approach, the considered imperfect geometry will lead to invalid and unreliable estimations of the real structure’s seismic response.

The growing interest in contemporary tile vaulting and the need to ensure its safety in seismic regions highlights the need to establish a more robust understanding of its seismic performance. An investigation of the effect of initial imperfections on complex-shaped, thin masonry shells clearly forms a step towards the achievement of this goal. In this paper, a study will be conducted to determine the extent to which initial imperfections influence the seismic capacity and seismic buckling load of an unreinforced, thin masonry shell structure using Finite Element (FE) modelling. The study focuses on the geometry of the Droneport Prototype, a shell structure that was built as part of the 15th International Exhibition of Architecture, at the 2016 Venice Biennale. Investigations are based on real imperfection data. These data will also be used to develop a design tool that will efficiently generate input for the modelling of tile vaulted structures with imperfections. The method used for the development of this tool will be presented. An examination of the sensitivity of buckling load to reductions in the design shell thickness will also enable identification of the extreme thinness limits at which seismic buckling becomes an issue.

2. LITERATURE REVIEW

2.1 Buckling analysis of thin masonry shells with imperfections

The influence of geometric imperfections on shell buckling phenomena has captured the attention of many researchers in the past. From the first experiments performed, very large discrepancies could be observed between the experimental and theoretical results (Hui-Shen, 2016), and it was not until the 1950’s which scientists discovered that the main parameter responsible for these discrepancies was the presence of geometric imperfections on the physical models (Schmidt, 2000). The method established to account for these discrepancies was to incorporate in the design, an empirical knockdown factor that could be used to reduce the predicted buckling load. This load could be obtained from a linear buckling analysis performed on the design shell geometry (Kriegesmann et al., 2012). By reducing the predicted load, the negative effect of initial imperfections on the load-carrying capacity of the structure could be taken into account, allowing for a more conservative prediction of the critical buckling load. However, the recommended knockdown factors, which are usually derived from experimental tests, cannot be representative of structures that are built using modern construction materials and manufacturing processes (Kriegesmann et al., 2012). It is therefore accepted that, the inclusion of the imperfection parameter in the numerical analysis will provide more realistic results (Papadopoulos & Papadrakakis, 2005). Several studies focused on the buckling response of thin shells with imperfections. However, these were restricted to singly curved forms (i.e. thin cylindrical panels and silo structures) which were mainly subjected to vertical compression loads [i.e. ref. Schenk & Schuëller (2003) and Papadopoulou et al. (2009)]. A few other studies have considered the buckling response of reticulated and monolithic concrete domes [i.e. ref. Dulacska & Kollar (2000), Mekjavić (2011)]. Relevant literature search on complex-shaped thin masonry shells that are subjected to vertical or lateral loads, yielded no results.

2.2 Modelling of initial geometric imperfections

Over the years, several approaches have been developed to describe the initial geometric imperfections numerically. Both, the deterministic and stochastic approaches aim to obtain a lower bound of the buckling load by considering the worst imperfection pattern (Kriegesmann et al., 2012). The consistent buckling mode method, the eigen-mode method and the Fourier decomposition method, fall into the category of deterministic approaches. In the consistent buckling mode method, the imperfection shape is the same, as the deflected shape of the structure at the stage prior to collapse. The deflected shape corresponds to the peak value of the load-displacement response diagram obtained from a nonlinear
analysis. In the eigen-mode method, the mode shape obtained from a linear elastic buckling analysis and which corresponds to the lowest buckling load is considered as the imperfection shape. The critical load can also arise from the linear combination of multiple eigen modes. The Fourier decomposition method was developed particularly for the modelling of imperfections in cylindrical shells. The imperfect geometry of the cylindrical shell is determined by a Fourier decomposition function which requires as input, the modal amplitudes and phase angles. These parameters are usually defined from experimental tests. In the stochastic imperfection method, the imperfection at each position on the structure is treated as a random variable and the imperfection field can be described from a normal distribution which has known statistical properties (Chen et al., 2016).

The stochastic representation of imperfections is more likely to provide realistic predictions of the critical buckling load, compared to the deterministic approaches. It is however important to specify a correlation between the imperfections that occur at two different positions in the structure as in reality, imperfections are not independent of each other. Instead, their magnitude is influenced by the construction method employed. Papadopoulos & Papadrakakis (2005) used an available imperfection data bank for thin-walled shells, based on which a correlation function was defined (Papadopoulos & Papadrakakis, 2005). Chen et al. (2016) proposed a model for the generation of correlated random imperfection fields in reticulated shell structures (Chen et al. 2016). The correlation of the imperfections occurring at two different joints could be determined based on the length and number of connecting members between the joints. The investigations were performed using real imperfection data of a reticulated shell structure. In this paper, the random imperfection model developed by Chen et al. (2016) is modified for its use in thin masonry shells. The initial imperfections of the Droneport Prototype geometry were determined based on data collected from on-site measurements of the real structure.

3. MODELLING THE IMPERFECTIONS OF THE DRONEPORT Prototype

3.1 Measuring equipment

To quantify the initial geometric imperfections which were present on the real shell structure, a FARO Focus3D x 330 laser scanner was used. The equipment can scan objects from 0.6m and up to 330m away, with an error ranging between +/- 2mm. It can automatically scan around 360º with a measuring speed which can reach up to approximately 976,000 points per second. The device scans a space field from a static position. A wave is sent out from a laser beam all over the field and whenever the laser hits a surface, the wave is reflected to the direction of the laser scanner. The measured distance between the surface and the laser scanner position defines the coordinates of the recorded points in space. To speed up the scanning process, a rotating mirror is used to control the scanning motion by guiding the laser into more than one directions. The origin of the coordinate system of collected points is the position where the laser meets the mirror. The data collected from a single scan were not sufficient to produce a complete model of the scanning structure, and hence multiple scans were taken from various positions, to ensure completeness of the data set. Each individual scan has its own coordinate system since the origin changes with the position of the laser scanner. To transform the coordinate systems of individual scans into a global coordinate system, it was necessary to define a spatial relation between different scanning stations. This was achieved by including in the scans reference objects which were fixed in space. The recorded data were processed into a single 3D point-cloud using Scene software package from FARO Technologies.

3.2 Point-Cloud Processing

The 3D point-cloud obtained from the processing of the laser scans (Figure 1) was reduced in size, by limiting the space field into the area of interest, which contains the Droneport Prototype (Figure 2a). The 3D point-cloud was further processed in CloudCompare; a freely available software for managing and comparing 3D point-clouds. The point-cloud was cleaned from all the unwanted objects and inaccurate scan points and it was then separated into thin slices, so that the top and bottom strips of each slice could be extracted.
Figure 1. View of the three-dimensional space field as recorded by the laser scanner

Figure 2. 3D Point-cloud of the Droneport Prototype (a) and the top (b) and bottom (c) surfaces as two separate points clouds
Once the process was completed for all slices, the top and bottom strips from all slices were stitched together to produce two separate point-clouds, representing the top and bottom surface of the shell structure, respectively (Figure 2b, 2c).

The top and bottom surface clouds could provide valuable information on the initial imperfections that are present on the Prototype. The thickness and shape imperfections are important sources of imperfection and are both considered in this study. The thickness variation throughout the structure could be estimated by comparing the top and bottom surface clouds, directly. The distance between the two clouds was calculated in CloudCompare based on the least-square best fitting plane. The method uses a plane to approximate the cloud surface locally, and the normal distance from that plane is measured. To quantify the shape imperfections, a mid-surface, which is the result of the average shape imperfections occurring at the top and bottom surfaces was generated. Comparison of the mid-surface with the design shell geometry, would determine the deviation of the structure from its ideal geometry.

![Figure 3](image)

Figure 3. Normal distribution of the (a) thickness and (b) shape imperfection fields

Due to the restricted view of the laser scanner at the various positions from where the measurements were taken, the data of certain regions in the structure were missing (Figure 2b). To obtain the imperfection data for these regions, the bottom surface was shifted at the elevation where the top surface was. The imperfection data were introduced in the FE model by associating each node of the FE mesh with a thickness and an error value representing the nodal displacements occurred due to the presence
of initial imperfections on the structure. The histograms of the thickness and shape imperfection fields are shown in Figure 3. The thickness imperfection field has a mean of 0.129m and a standard deviation of 0.013m whereas for the shape imperfections the mean and standard deviation were -0.042m and 0.034m, respectively.

Figure 4. Contour plot of the actual initial thickness imperfections of the Droneport Prototype

Figure 5. Contour plot of the actual initial shape imperfections of the Droneport Prototype
The measured thickness and shape imperfections were also presented visually using 2D-contour plots. To produce these plots, the GridFit function written by D’Errico (2007) was implemented in MATLAB. The function takes the scattered laser scan data and projects them into a pre-defined grid of points. The contour plot is generated by splitting each cell in the grid into triangles, and by then performing an interpolation within the triangles. The resulting plot is dependent on the interpolation scheme selected, the solver used for the resulting system of equations, the grid spacing, and the degree of smoothening applied to the grid data. In this study, the imperfection plots were produced using linear interpolation and a smoothening factor of 20. Since the resulting imperfection plots were very sensitive to the smoothening factor, a reasonable guess had to be made so that the required level of detail could be obtained. The contour plot obtained for the thickness imperfections (Figure 4) shows that the thickness of the real structure ranges between approximately 10 to 15 cm as opposed to the design shell thickness of 12 cm. As regards to shape imperfections, a zero value in the contour plot (Figure 5) denotes that the point rests on the ideal surface. Positive and negative values indicate that a point in the structure resides above and below the ideal surface, respectively. The plot of shape imperfections suggests that the imperfections do not occur randomly. There are certain regions in the structure whose deviation from the design geometry is greater in magnitude compared to the rest of the structure, such as at the edges and at the areas where there is a change in the curvature from positive to negative. The points which were produced at the corners of the rectangular grid do not exist in reality, and for this reason, the imperfection values for each of these points, were set to zero. However, it was observed that the interpolation between data was influenced by that change significantly, and the resulting spatial distribution of imperfections was different from that initially obtained. Since the contour plots produced initially were in a good agreement with the plots obtained in CloudCompare, these were considered.

**4. SEISMIC ANALYSIS OF THE DRONEPORT PROTOTYPE**

*4.1 Nonlinear pushover analysis*

Once the initial imperfections of the Droneport Prototype were quantified, a preliminary analysis was conducted to investigate how and to what extent, the presence of initial imperfections influences the seismic behavior of the structure. The effect of initial imperfections on both, its seismic capacity and seismic buckling load were examined. A nonlinear static (pushover) analysis was initially performed using DIANA software package, on both, the design, and the imperfect geometries. Each source of imperfection was treated as a stand-alone case to enable quantification of the effect of each component, individually. The combined effect of the thickness and shape imperfections was not considered in this study. In the pushover analysis, a monotonically increasing lateral load, which was proportional to the mass of the structure was applied in the direction indicated in Table 1. For the modelling of cracking in masonry, a total strain crack rotating model was implemented in the analysis. A linear stress-strain relationship was used to describe the tensile softening behaviour of masonry, whereas in compression, an ideal elasto-plastic behaviour was assumed. The physical and material properties of the Prototype and the input parameters used in smeared cracking, are shown in Table 1.

<table>
<thead>
<tr>
<th>Physical properties</th>
<th>Plan dimensions</th>
<th>8m x 10m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design thickness</td>
<td>12cm</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material properties</th>
<th>Young’s Modulus, E</th>
<th>3 GPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, ρ</td>
<td>1900 kg/m³</td>
<td></td>
</tr>
<tr>
<td>Poisson’s ratio, ν</td>
<td>0.2</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Smeared crack model properties</th>
<th>Tensile strength, f_t</th>
<th>0.35 MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive strength, f_c</td>
<td>8.5 MPa</td>
<td></td>
</tr>
<tr>
<td>Fracture energy, G_f</td>
<td>95 N/m</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: The finite element mesh of the Droneport prototype with its physical and material properties.
The plots of horizontal displacement and base shear were obtained for both sources of imperfection and they were compared with the plots obtained for the design geometry (Figure 6). Figure 6a show that the real structure has a seismic capacity which is about 13% greater than that obtained for the design geometry. This occurs because the mean of the thickness variation on the real structure was approximately 13cm, which is still greater than the design thickness. In the case of shape imperfections (Figure 6b), a substantial reduction in the seismic capacity of the structure was expected, due to the significant shape variations observed throughout the structure. However, the estimated seismic capacity for the perfect and imperfect geometries do not differ significantly. In this case, the combined action of the two imperfection sources considered would have provided more comprehensive results.

![Pushover curve at the top node of the FE mesh](image1)

![Pushover curve at the top node of the FE mesh](image2)

Figure 6. Pushover curves obtained from the seismic analysis of the design shell geometry and the shell geometry with imperfections

### 4.2 Elastic buckling analysis

Subsequently, a linear buckling analysis was performed on the design and imperfect shell geometries. A seismic load was applied on the FE models. The magnitude of the applied lateral load was equivalent to the maximum load that was sustained by the structure before collapse in the pushover analysis ($F_{pushov}$). From the buckling analyses performed, the buckling modes and their corresponding buckling load factor, $\lambda$ could be determined. The buckling load factor could then provide an estimation of the critical load at which buckling occurs by using Equation 1, where $F$ is the applied load ($F = F_{pushov}$) and $F_{crit}$ is the critical buckling load. A buckling factor which is less than unity denotes that the structure will fail due to buckling failure.

$$\lambda = \frac{F_{crit}}{F}$$  \hspace{1cm} (1)

A comparison of the results presented in Table 2 show that the structure has sufficient seismic buckling capacity so that it is more likely to fail due to the formation of a failure mechanism, rather than due to buckling phenomena. The buckling response will dominate collapse, only if the seismic load applied is about seventeen times greater than that currently applied. A comparison between the buckling load obtained for the design geometry and the imperfect geometries has shown that seismic buckling will be reached at an earlier stage on the imperfect geometries. The first two buckling modes of the design geometry are shown in Figure 7.
Table 2: Comparison of seismic capacity and buckling load the shell structure

<table>
<thead>
<tr>
<th></th>
<th>Base shear (g)</th>
<th>Seismic capacity, $F_{pushov}$ (kN)</th>
<th>Buckling load factor, $\lambda$</th>
<th>Buckling load, $F_{crit}$ (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Design geometry</strong></td>
<td>0.41</td>
<td>109.5</td>
<td>18.66</td>
<td>2043.27</td>
</tr>
<tr>
<td><strong>Non-uniform thickness</strong></td>
<td>0.45</td>
<td>99.7</td>
<td>15.54</td>
<td>1750.73</td>
</tr>
<tr>
<td><strong>Shape imperfections</strong></td>
<td>0.39</td>
<td>95.2</td>
<td>15.46</td>
<td>1757.39</td>
</tr>
</tbody>
</table>

![Buckling mode 1 ($\lambda_1$=7.65)](image1)  ![Buckling mode 2 ($\lambda_2$=7.73)](image2)

Figure 7. The first two buckling modes of the perfect FE model when subjected to 1g lateral loads and their corresponding buckling values.

5. GENERATION OF IMPERFECTION PATTERNS

To examine the effect of initial imperfections on the buckling response of the Droneport Prototype, different imperfection patterns had to be considered. The generation of the various imperfection patterns required for this investigation was achieved by adapting the method developed by Chen et al. (2016) for its use in thin masonry shells. The method uses the random field theory to describe the random variation of imperfections throughout the structure. The method is based on the principle that the imperfections at two different locations can be mutually correlated, since the imperfection of one node can affect the imperfection of adjacent nodes. Based on this principle, a tool has been developed which generates numerical samples of spatially correlated fields. Initially, the tool generates uncorrelated random variables which are then transferred into a correlated random field. The following paragraphs provide an analytical description of how these imperfection fields were generated.

A relationship of the correlation between imperfections at two different locations in the structure could be defined using the measured imperfection data obtained from the contour plots. First, the extrema points of the imperfection data field were extracted. The extrema points would enable determination of the spatial distribution of imperfections throughout the shell surface, by considering parameters such as the geometric amplitude and wavelength of imperfections. The statistical properties of the extrema points were compared to the imperfection field obtained from the laser scans. The results showed that the mean and standard deviation of the original thickness imperfection field, which were estimated to be 0.1287m and 0.0132m respectively, were approximately the same to the estimated mean (0.1281m) and standard deviation (0.0134m) of the reduced-in-size thickness imperfection data field. Similarly, the mean and standard deviation of the original shape imperfection field were 0.0013m and 0.0767m respectively, while for the peak thickness values, these were 0.0014m and 0.0381m. The spacing between the extrema points could also be calculated by generating linear elements between them, using Delaunay triangulation and by then calculating the lengths of connecting members (Figures 8 and 9).
For each source of imperfection, the extrema points were separated into groups, depending on the calculated distance between pair of points. Each group of points was sub-divided into $G_i$ and $G_j$ groups containing the $i$ and $j$ components of the $n$ unique pair of nodes, i.e. the coordinate points $(x_i,y_i)$ and $(x_j,y_j)$ of nodes $i$ and $j$ respectively, and the imperfection field for each group $I_{G_i} = \{I_{G_i1}, I_{G_i2}, I_{G_i3}, ..., I_{G_i n}\}$ and $I_{G_j} = \{I_{G_j1}, I_{G_j2}, I_{G_j3}, ..., I_{G_j n}\}$. Based on this data, an empirical correlation coefficient, $\rho$, could be obtained for each group of points, using Equation 2. $I_{G_i k}$ and $I_{G_j k}$ represent the imperfections of nodes $i$ and $j$ respectively, for the node pair $k$ ($1 \leq k \leq n$) and $\sigma_{G_i}$ and $\sigma_{G_j}$ represent the empirical standard deviation of $G_i$ and $G_j$.

$$
\rho = \frac{\sum_1^{n} I_{G_i k} \cdot I_{G_j k}}{n \cdot \sqrt{\sigma_{G_i}^2 + \sigma_{G_j}^2}}
$$

(2)

The calculated correlation coefficients were plotted against the average of the distance range considered for each group, and an exponential correlation function could be obtained in the form of $f(x) = A \cdot e^{Bx}$ by fitting an exponential curve. The exponential function established could be used to describe mathematically the correlation between any pair of nodes in the FE mesh. It should be noted that not all the estimated correlation coefficients were used to produce the correlation functions, as the imperfections of the pair of points which their distance was exceeding the 3m, were weakly correlated. The matrix decomposition method could then be used to generate the random imperfection fields. This would require the construction of the $S_{ij}$ matrix, the components of which, represent the measured spacing between node pairs. The correlation matrix could then be estimated using the exponential function shown in Equation 3, where $D = 1/B$ and $A$ and $D$ are the scaling parameters obtained earlier.

$$
\rho_{ij} = A \cdot e^{S_{ij}/D}
$$

(3)
The covariance matrix could also be estimated by assuming that the imperfection field is weakly homogeneous. This means that the mean, \( \mu \) and standard deviation, \( \sigma \) are the same at any nodal position (Equation 4).

\[
C_{ij} = \sigma^2 \cdot \rho_{ij}
\]  
(4)

A Cholesky factorization of the covariance matrix \( C \) was then be performed. The method was used to decompose a symmetric, positive-definite matrix into a lower triangular matrix, \( L \) and its conjugate transpose (Equation 5).

\[
C = LU = LL^T
\]  
(5)

The lower triangular matrix, \( L \) was multiplied with an n-dimensional vector of an uncorrelated variable \( \alpha \), which is a zero-mean, uni-variate random field. The correlated imperfection field, \( r \) was obtained using Equation 6, where \( \mu \) is the mean of the original imperfection field.

\[
R = L \cdot \alpha + \mu
\]  
(6)

6. EFFECT OF VARIOUS IMPERFECTION PATTERNS

The preliminary analysis presented in Section 4 was extended to investigate the effect of various imperfection patterns on the seismic capacity and buckling load of the shell structure. The buckling analysis results obtained from analyses with different shape and thickness imperfection patterns are presented in Table 4. In each analysis, the seismic load corresponding to the peak load obtained from the pushover analysis was applied. A comparison between different buckling load factors demonstrates that imperfection patterns which have the same statistical properties do not have significant impact on the buckling capacity of the structure. In all cases, the buckling load factors are lower than that obtained for the design geometry. This is a proof that the presence of imperfections might affect the buckling response of the structure, but not significantly in the case of the Droneport Prototype. Furthermore, the seismic buckling capacity range obtained for the shape imperfection patterns is generally lower than that obtained for the thickness imperfections. This is reasonable as a slight variation of the thickness field cannot affect much the position of the thrust line within the structure. However, a slight change in the shape of the structure is likely to cause changes in the tension and compression zones.

<table>
<thead>
<tr>
<th>Thickness imperfections</th>
<th>Buckling load factor, ( \lambda )</th>
<th>Shape imperfections</th>
<th>Buckling load factor, ( \lambda )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imperfection pattern</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TR1</td>
<td>16.41</td>
<td>SR1</td>
<td>15.76</td>
</tr>
<tr>
<td>TR2</td>
<td>17.23</td>
<td>SR2</td>
<td>15.50</td>
</tr>
<tr>
<td>TR3</td>
<td>17.91</td>
<td>SR3</td>
<td>17.08</td>
</tr>
<tr>
<td>TR4</td>
<td>18.17</td>
<td>SR4</td>
<td>17.23</td>
</tr>
<tr>
<td>TR5</td>
<td>17.06</td>
<td>SR5</td>
<td>17.41</td>
</tr>
</tbody>
</table>

6. BUCKLING SENSITIVITY TO DESIGN SHELL THICKNESS

The sensitivity of buckling load to reductions in the design shell thickness was also investigated. The buckling load was obtained for when the structure was subjected to lateral loads which their magnitude was equal to 0.45g. The corresponding buckling load factors obtained for each shell thickness are presented in Table 5. The results have shown that the buckling load factors reduce gradually as the thickness decreases, and that the design shell geometry will fail due to buckling phenomena when the
thickness is reduced to 1cm. This is a proof that the shell structure has significant flexibility and sufficient ductility to resist very large deformations without failing.

Table 5: Buckling loads obtained for analyses with different thicknesses

<table>
<thead>
<tr>
<th>Thickness (cm)</th>
<th>12</th>
<th>11</th>
<th>10</th>
<th>9</th>
<th>8</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buckling load factor, $\lambda$</td>
<td>17.00</td>
<td>14.90</td>
<td>12.94</td>
<td>11.12</td>
<td>9.43</td>
<td>7.88</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Thickness (cm)</th>
<th>6</th>
<th>5</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buckling load factor, $\lambda$</td>
<td>6.45</td>
<td>5.10</td>
<td>3.79</td>
<td>2.59</td>
<td>1.48</td>
<td>0.59</td>
</tr>
</tbody>
</table>

7. CONCLUSIONS

In this paper, the effect of initial geometric imperfections on the seismic capacity and seismic buckling load of an unreinforced, thin masonry shell structure was examined, using finite element modelling. The modelling of initial imperfections was based on the stochastic imperfection method and on real imperfection data. The data were obtained from on-site measurements of the real shell structure using a laser scanner. An imperfection modelling tool was developed for the generation of correlated random imperfection fields which uses as input, the statistical properties of the real imperfections. A preliminary analysis was first conducted to investigate the effect of the measured initial imperfections on the seismic response of the structure. The analysis was extended to quantify the effect of different imperfection patterns. For both cases, a nonlinear pushover analysis and a linear buckling analysis were performed. Comparison between the seismic capacities obtained from the pushover analysis and the critical buckling loads have demonstrated that the shell structure is likely to fail due to the formation of a failure mechanism, rather than due to buckling. To obtain more reliable and accurate results, the proposed method for the modelling of initial imperfections needs to be improved in the future. In addition, the combined action of the thickness and shape imperfections on the seismic response of the structure is an important parameter which will also need to be considered.

8. REFERENCES


