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The Effect of Initial Geometric Imperfection on the Load Bearing Capacity of Double Layer Barrel Vault Space Structures

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Abstract. *The existence of some geometrically imperfect members in space structures are almost inevitable, beside that there are some imperfections in botching the structures and the fact that they are effective in producing internal forces is undeniable. When a compressing member yields, in spite of that, continues bearing a lot of load, on the other hand the buckled compressive member goes to a critical situation and losses its stiffness and shed its load on the other members, causing a progressive collapse. Double layer barrel vaults which have statically highly indeterminate degree , may cause this phenomena because of unsuitable members .As the members initial curvature is the most popular geometric imperfection which is common in practical structures , in this thesis has chosen as an effective imperfection ,for research. We have tried to study this effect on the load bearing capacity of model structure. The selected model is a double layer barrel vault which is subjected to uniform concentrated load applied vertically downward to each node of the upper layer and members assumed to be pin-ended .The ratio of pure height of structure to pure opening mouth is 0.22 and the kind of layers decoration is a square on square. Two forms of analysis carried out; one for monotonous imperfections and the other for 30 cases of random imperfections which based on Monte Carlo Methods. After analysis, the ratio of maximum reduction to common case was about %41, also the suitable way of certain conclusion is presented with Monte Carlo Method.*

1 INTRODUCTION

Double layer reticulated structures are generally indeterminate from statically point of view. As occasionally there will not be any problem in stability and structure efficiency even with elimination of structure elements 15% to 25%, sometimes this preconception causes the engineers misleading about the estimation of structure safety factor [9] When one of the compressive element yields, truss stiffness decreases. After the buckling of compressive element, its force is shed among the other elements [3]. Consequently other bars are buckled and lead to progressive collapse phenomenon which imposes impact dynamic effect on the structure [2, 4]. While the development of double-layer reticulated shells on the architectural /executive ground, the buckling issue of such structures has not completely solved yet. Reticulated shells have the same specification with the reticulated and shell structures, so they will encounter with both structures problems and these problems will resonate and combine [7]. In a truss system, the structure elements are essentially under the axial forces and the element of the structures may be collapsed either under being yield of tension or buckling under compress. If one of the elements of the structure buckles the behavior of its element will conform the post critical characteristics [5, 12]. So in the case of determining behavior of tensional and compressive elements after reaching the critical load, the structure can be analyzed and continue the analysis until the overall collapse of the structure occur. On the other hand, having post critical characteristics the behavior of tensional and compressive element of the structure analysis will be possible between the ranges of the first local buckle to the total structure buckling. Usually when a tensional element reaches yield load, its load capacity increases somehow due to strain hardening [8], but when a compressive element buckles load capacity decreases with increasing axial shortening. I.e., the element cannot resist and consequently sheds its load into the other structure elements. The stiffness of post buckling compressive element has an effective influence on the total behavior of the element. It means that, if compressive element becomes unstable and abruptly shed its load to the other elements, its effect will be worse than when the load gradually sheds on the other elements [6]. Presentation of the compressive element behavior has an essential role in the buckling analysis. In the most buckling methods, first of all the load-displacement behavior of compressive element should be determined, and then the results can be used in the modeling of nonlinear compressive elements behavior. Hence, in order to determine the compressive element behavior, the behavior of post buckling element should be determined. There will be three collapse mechanisms for the structures as mentioned below: overall collapse, local collapse with dynamic snap through, local collapse without snap –through [2].

The essential factors in determining compressive buckling element and general structure behavior are the material and the geometric imperfections and there are several geometric varieties such as: nodal imperfections, increase or decrease in element length rather than desired length and element initial curve which is considered as an effective imperfection. In fact the imperfection effect of capacity rather than double layer barrel vault space structure is the main problem of this study. Fundamental theory of this study is based on the existing geometric imperfection which causes the decrease in load capacity and overall /local instability. In this study as double layer barrel vault load increases incrementally in top nodes of double layer grid, the load bearing capacity of the structure decreases. Also, distribution of existing imperfection has been done randomly. In the distribution of imperfect elements in the critical area Monte Carlo analysis standards [16] has been considered. Finally, in order to determine safety factor for structures load bearing capacity a new method is offered.

2 SPACE TRUSS FOR OBSERVATION AND ANALYTICAL METHOD

As the element of the space trusses are usually manufactured in factory, involving some nonstandard products about 1% of space trusses. In order to simplifying the study five types of imperfections for elements are use. Of course, practically due to the diversity of imperfection elements, the distribution will be continuum based on gamma distribution.

2.1 Modeling

The double-layer barrel vault truss includes the pin-ended connections. The dimension of the structure plan is 20*21.3 meters which is almost square on square. The distance between two layers is 1.63meter.also; the ratio of net height to net bay is 0.22. Double-layer grid is designed as all of the lower and upper elements have 2 meters length with a diagonal 2.4 meter length. In this model internal length of structure is 4.42 meters and net bay is 19.38 meters. (Figure 1)

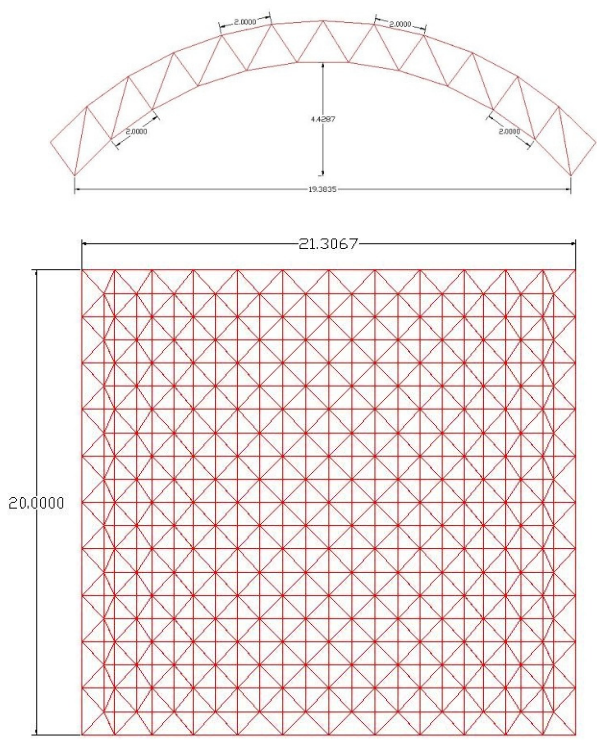


Figure1. Layout of studied space trusses

2.1.1 Material specifications

The material is steel and its yield stress is 360 Mpa and yang module is 210000 Mpa.

2.1.2 Elements specifications

Regarding to 1.5 ton/joint loading for all upper layer nodes and the structure linear analysis, all profiles are selected from steel tube with an external radius of 41.275mm and a wall thickness of 9.52 mm.

2.1.3 Imperfection specifications

The kind of used imperfection is geometrical imperfection with an initial deviation [5]. The maximum initial deviation of the member at mid-point from the chord line was taken to be ε.

2.1.4 Computer program specifications

In order to carry out nonlinear pre-buckling and post-buckling analysis, Lusas software including BM3 for compressive element modeling has been used. [1]

2.1.5 Loading specification:

The starting point of incremental loading is 100N and has been continued until structure collapse. (Figure2)

2.1.6 Supporting specifications:

All of the supports are pin-ended and positioned along with the lower layer edges. (Figure2)

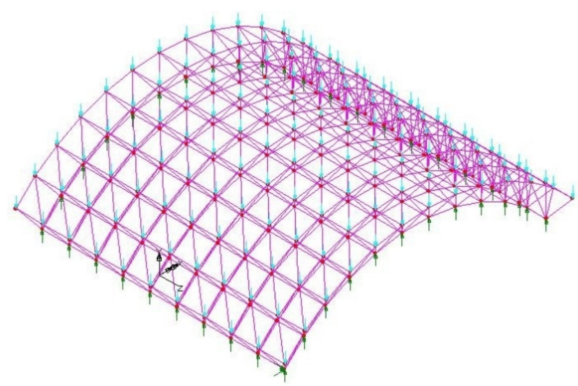


Figure2. Truss loading & linear edged support position

2.2 Determining the buckling behavior of compressive element in a finite element method

In order to do nonlinear analysis of the modeled structure, determining load-displacement relationship in pre-buckling and post buckling stage of structural members with consideration of its imperfection is essential [5]. Applying tubular profile in the space structures is typical. So as it already mentioned, using linear analysis, profile sections with the 41.275mm radius and with the wall thickness of 9.52mm in the 2.4 and 2 lengths have been selected.

2.2.1 The assumptions of analyses of compressive elements in the finite element method are:

-Complete elasto-plastic stress-strain relationship for material is considered and regardless of hardening effect, we assume symmetric relationship for stress-strain diagram. [4]

-We assume the element section prismatic and symmetric.

-We generalize each element to ten equal parts to achieve precious and reliable results.

-We use the Kirchhoff thin beam model to determine the behavior of the compressive elements regardless of the shear deforming effect.

-If the compressive elements become straight with homogenous material, pure compressive condition will be occurred. But there would not be any ideal compressive elements with the mentioned characteristics. Somehow some imperfections such as the following ones may create bending moment in the compressive elements and decrease the load bearing capacity.

-Initial element deviation, eccentric loading, diversity of local specifications, being inhomogeneous, residual stress in element section

-In this study merely the compressive element initial curvature as a geometric imperfection has been considered. It is assumed that, maximum initial deviation of the member at mid-point from the chord line was taken to be ε and it is symmetric as well. For imperfection (ε=0.0005L, ε=0.001L, ε=0.005L, ε=0.01L and ε=0.02L), the elements behavior have been determined.

-We assume that compressive elements do not have local instability. In order to determine compressive element load-displacement relationship; we can use a statically large deformation elasto-plastic nonlinear analysis and both material and geometric nonlinearity in analysis have been used [7]. (Figure3)

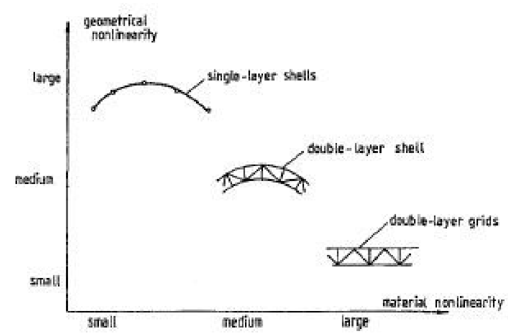


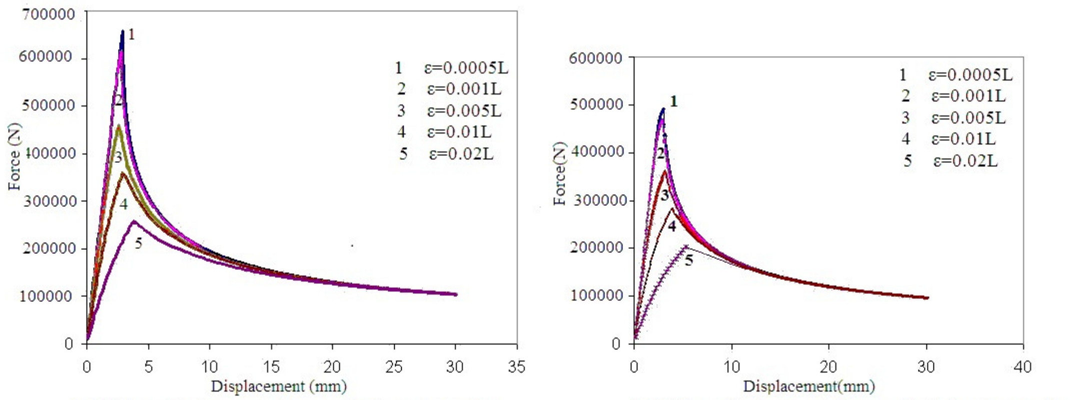
Figure3. Effects of nonlinearities

-Drawing an equilibrium nonlinear route until reaching the buckling load has been done by Newton-Raphson repetitive method as this method has been diverged due to being singular stiffness matrix adjacent to buckling critical point; consequently it would not be efficient. So, in order to draw balanced route adjacent with critical point, we have used arc length method.

-The quantity of compressive element critical load is calculated for member initial maximum imperfection and the obtained quantities will be reliable if the load is less than Euler buckling load. Otherwise, the initial buckling load will be considered.

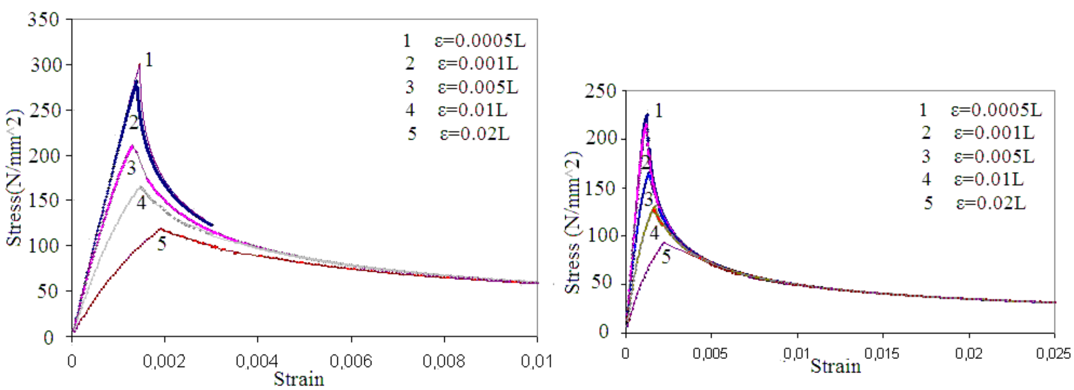
2.2.2 Drawing stress-strain relationship based on the above assumptions

Members length has been analyzed with the imperfections (ε=0.0005L, ε=0.001L, ε=0.005L, ε=0.01L and ε=0.02L) and all behavior were compared [10, 11]. The slenderness of the elements is medium and stress-strain curvature has been calculated according to the force-displacement which their diagram have been illustrated below. Note that, sometimes the above diagrams have been illustrated based on 1000 case of incremental loading. Determining of these points to structure analysis for finite elements program may be time consuming. In this study nonlinear curves have been considered in calculation with 6 points. (Figure 4, 5)



Axial force-displacement diagram for 2meters member   Axial force-displacement diagram for 2.4meters member

Figure4. Axial force-displacement diagram for 2and 2.4 members



Stress-strain diagram for 2 meters member   Stress-strain diagram for 2.4 meters member

Figure5. Stress-strain diagram for 2and 2.4 members

According to the depicted diagrams, it is clear that the applicable elements behaviors are brittle. Hence, final strength of such elements has been decrease with increase in the imperfection as a result ductile behavior is formed.

2.3 Double layer barrel vault truss analysis

Analyze the barrel vault in two manners. Firstly under uniform imperfection for all elements and secondly under random imperfection about 30 cases

2.3.1 Analyzing under uniform imperfection for all elements

Study the truss under Quadra imperfections (ε=0.0005L, ε=0.001L, ε=0.005L, ε=0.01L).it is assumed that, all of the elements have the same imperfection and the result of the analysis have been drawn in a displacement-load diagrams. It is clear that, with increasing the imperfections quantity in a current mode, total structure strength is influenced effectively. (Figure 6)

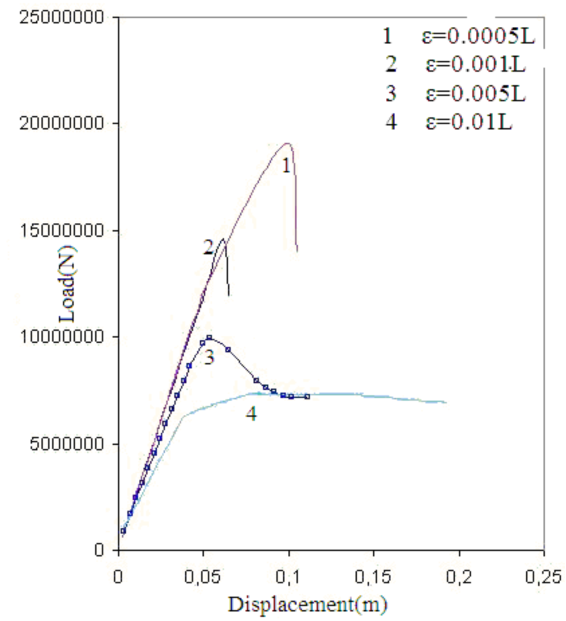


Figure6. Behavior of the truss under uniform geometrical imperfections

2.3.2 Analyzing truss under random imperfections distributions

Due to being time consuming of nonlinear analysis and likelihood of all possible imperfections, 30 analysis cases based on Monte Carlo standards have been used to estimate load capacity. For each analysis, consider a different distribution for imperfections consequently; use a program in visual basic to determine the random imperfections distributions. Note that, the purpose of complete status or comparative standards, is (ε=0.001L) total imperfections for all elements. Also as linear analysis result show that, lower layer and diagonal elements cannot reach the plastic stage so they would not be critical. Consequently critical area is selected in the critical area of truss upper layer. (Figure7)

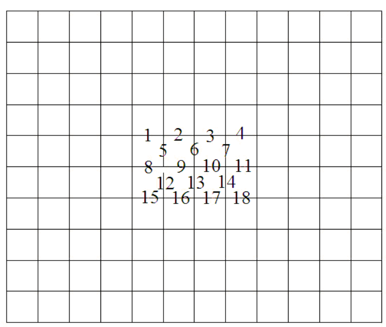


Figure7. The position of randomly distributed elements of the truss top layer in the critical area

2.3.2.1 The method of determining the quantity of each existing imperfection

The quantity of each existing imperfections resulting from gamma distribution has been selected [13] according to the following diagram. (Figure8)

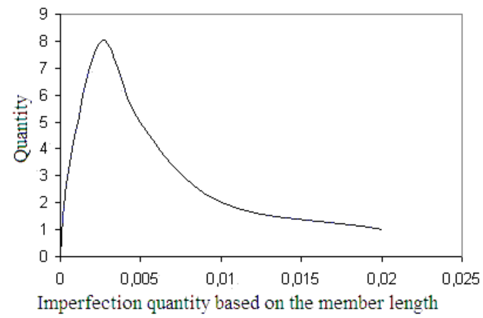


Figure8.Quantity-imperfection diagram via gamma distribution

2.3.2.2 Consideration of random analysis result

We compared the obtained results of random analysis to achieve the quantity of strength decline according to changes in imperfection elements locations. (Figure9)

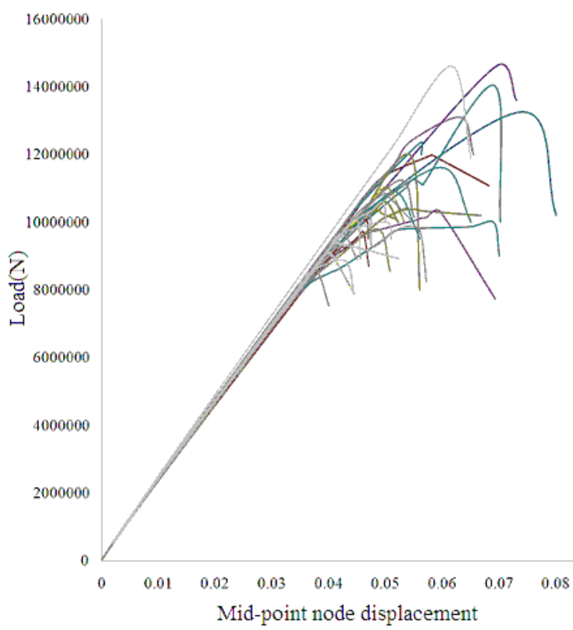


Figure9. Node mid-point Load-displacement behavior for 30 random and a perfect modes

2.3.2.3 The structure sensitivity

The structure sensitivity rather than imperfection distribution of truss in the critical area is completely evident. According to the analysis, the strength average of structure for different conditions is 10795004.07 N and strength decline diagram is drawn based on random analysis. (Figure10)

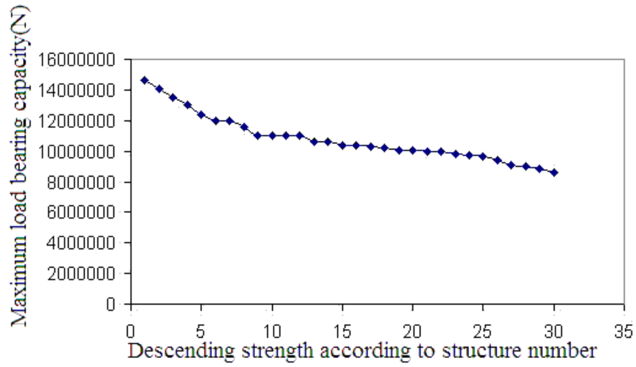


Figure10. Descending strength according to structure number

According to analysis based on Monte Carlo criteria and its accordance with normal distribution the diagrams are

1-frequency-strength related to quantity of resulted strength. (Figure11)

2-probability density function diagram

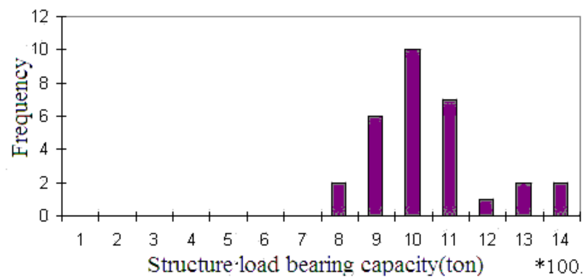


Figure11. Histograms of the structure load bearing capacity for 30 random analyses

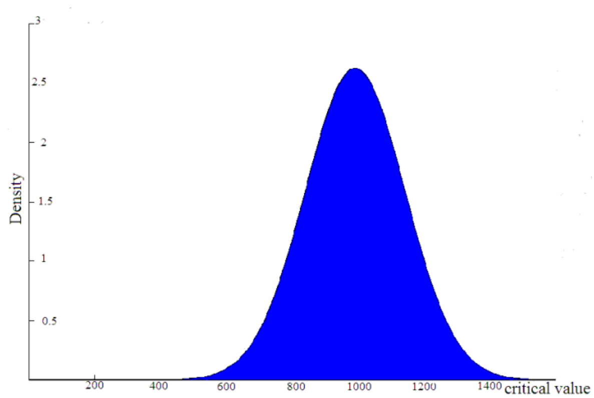


Figure12. Analysis density distribution function

As a result based on the illustrated diagrams and regarding to the possibility of desired occurrence, estimating of the structure strength would be possible. This method for determining safety factor has been mentioned in [14], [15] references.

3 SUMMERY AND CONCLUSION

According to the analysis, we conclude that:

-The applied imperfections in the critical area have not have a remarkable effect on the structure initial stiffness. Indeed, the most important effect of such measurements is decreasing the maximum load bearing capacity.

-The double layer barrel vault space structure is sensitive to geometric imperfections.

-For different modes of randomly imperfections distributions, in the worst mode the structure has shown 41% strength decline.

-In this study the only geometric imperfections is initial deviation contributed in the result. Furthermore, the other imperfections effect and the combination of the local instabilities have not been considered. Randomly distribution of the imperfections in the critical area based on Monte Carlo method, leads to finding a suitable method way to estimate the structure actual and practical strength.

-Based on the analysis of Monte Carlo method and drawing related curvature (including strength-possibility and frequency-strength), the possibility of desired strength occurrence is assessed.

4 RECOMMENDATIONS

The main logical method in such structures, having more accuracy in manufacturing and controlling the parts before assembly. So, if there are more member imperfections, they should not be used in the compressive critical area. In the double layer barrel vault space structure, the critical member located in upper layer and these members are much more sensitive to the geometric imperfection; so, more strengthening the members in the critical area of the truss leads to increasing the structure load bearing capacity and decline the structure sensitivity to the imperfection as well. In summary it is not possible to monitor the structure in all conditions so, it is recommended to apply fuzzy logic and artificial neural network in future studies.

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