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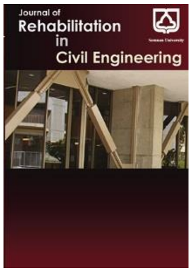

Probing the Probabilistic Effects of Imperfections on the Load Carrying Capacity of Flat Double-Layer Space Structures

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ABSTRACT

Load carrying capacity of flat double-layer space structures majorly depends on the structures' imperfections. Imperfections in initial curvature, length, and residual stress of members are all innately random and can affect the load-bearing capacity of the members and consequently that of the structure. The double-layer space trusses are susceptible to progressive collapse due to sudden buckling of compression members. Progressive collapse is a chain of local failures leading to the collapse of either the entire or a part of the structure. In this paper, the effects of the probabilistic distribution of initial curvature and length imperfections on the bearing capacity of flat double layer grid space structures for different member's length and support conditions have been studied. First, equal to the number of the members of the structure, two sets of random numbers have been generated using the Gamma and Gaussian distributions to account for the initial curvature and the length imperfections, respectively. Thereupon, the amount of the imperfection randomly varies from one member to another. Afterward, based on the Push-Down analysis, the ultimate load-bearing capacity of the structure was determined through nonlinear analyzes performed through the OpenSees software and this procedure for certainty was repeated numerous times. Finally, based on the Monte Carlo simulation method, the structure's reliability diagrams and tables were procured. The acquired results indicate that the behavior of flat double-layer space grids are sensitive to and can be affected by the random distribution of initial imperfections.

1. Introduction

The fact of the existence of initial geometric imperfections of a structural system and its individual members is one of the factors contributing to the nonlinear behavior of the structure and is taken into account in advanced analysis and design of space trusses. Flat Double-Layer Space Trusses (FDLST) are efficient for covering large areas. They are usually redundant and therefore are expected to remain stable once a member fails. However, the sudden collapses of different space trusses such as Hartford Civic Center, Connecticut, USA, in 1978 [23] and similar observations [21] challenged the validity of this assertion. The load which collapsed the Hartford Civic Center roof structure was approximately half of the expected collapse load. Such observations implied that, in particular cases, local failures may lead to the collapse of the entire structure. The FDLSTs' collapse behavior is highly affected by many behaviors [24], among which the sudden buckling of the compression members is a crucial behavior that may lead to the occurrence of progressive collapse. If a compression member buckles, it will distribute its load to the adjacent members. If the adjacent members withstand the distributed loads, the failure will remain locally contained; otherwise, the failure propagates throughout the structure leading to progressive collapse.

Tests and studies performed on these structures [5, 6, 7, 8, 20] point out the sensitivity of these structures to the existence of different imperfections. These studies show that the high indeterminacy of these structures cannot ward off the progressive collapse in the structure and even the buckling of one critical compressive member due to overloading may very well apply so strong a force to the adjacent members that can launch the progressive collapse in the structure.

Many studies [2, 12, 13, 28, 29] have shown that initial geometric imperfections have a significant influence on the strength of shell and space structures. Even a small amount of initial geometric imperfection may lead to a reduction of over 50% in the load-carrying capacity of the structure.

A number of basic methods have been developed to model the geometric imperfections of reticulated shell and space structures over the past three decades, including the consistent buckling mode method [3], the eigenmode method [9], the Fourier decomposition method [4], and the random imperfection method [27]. In the consistent buckling mode method, the perfect structure is first analyzed by a nonlinear analysis and the nodal displacement increment at the state of incipient collapse is used to represent the mode of the initial imperfection in a subsequent nonlinear analysis. The eigenmode method assumes the imperfect structure has initial displacements in the shape of the elastic critical buckling mode of the structure. In both methods, the initial displacement of the structure is scaled such that the maximum nodal imperfection is equal to a prescribed value, which is L/300 in the current Chinese Specification [25] where L represents the largest horizontal dimension of the structure. Fourier decomposition method has been used to interpret the imperfections of cylindrical shells [11]. Imperfect surface of a cylindrical shell is described by a series of modal amplitudes and phase angles. Determination of modal amplitudes and phase angles in the Fourier series function requires extensive measurement data, which is often not available in practice. The random imperfection method recognizes that the initial geometric imperfection is uncertain by its nature. The imperfection at a node is modeled as a random variable. It has been suggested that a normal random variable with a zero mean and a standard deviation equal to half of the construction tolerance can be used to model the nodal geometric imperfection [22]. Samples of imperfect structures can then be generated using Monte Carlo simulation. The minimum value of the strengths of these imperfect structures is taken as the design load-carrying capacity of the structure.

Initial curvature and length imperfections are amongst the most common kinds of imperfections in truss structures. The existence of these types of imperfection in members causes the development of initial stresses in the members of the structure and also changes the distribution pattern of the internal forces of the structure's members. This can ultimately cause an alteration in the collapse behavior and load bearing capacity of this type of structure compared to the perfect structure.

Although researchers have paid the due attention to the effects of random distribution of imperfections on the load bearing capacity and collapse behavior of space structures but up until now, no comprehensive study has been conducted with regards to the effects of simultaneous geometrical imperfections such as length and initial curvature in flat double-layer space structures. In this paper, the effects of initial curvature and length imperfections on the capacity of double-layer grids have been simultaneously and probabilistically investigated. The possibility of the occurrence of imperfections in all the members of the structure has been taken into consideration and the structure's reliability for different support conditions has been determined by employing the Monte Carlo simulation method. In the presence of hundreds of random variables and with the nonlinear behaviors in space structures being considered, performing random analyzes and determining reliability are quite bulky and time consuming tasks which have been carried out in this study. All the structural analyzes have been performed by programming in the OpenSees finite element software [14, 15].

2. Reliability and the Monte Carlo simulation method

The Monte Carlo method is also called the statistical testing method. It can be used to solve practical engineering problems containing random variables by numerical simulation and probability statistics [19]. The probability distributions of the important parameters in the problem can be established based on the results of numerical simulation. These distributions can be used to generate samples of numerical data [18]. It is considered that the results of the Monte Carlo method are credible as long as the simulation tests are accurate and a sufficient number of sums are undertaken.

Reliability is defined in terms of the performance of a member or a structure. This performance can be defined in different levels such as the perfect or the relative performance of the system. In any case, if P_f is considered as the possibility of failure, the reliability R_e can be defined as follows [16, 17]:

$$R_e=1-P_f \tag{1}$$

To calculate the reliability of a system, the limit state function can be presented as follows:

$$LSF=R-S \quad (2)$$

Where R and S are the strength of the system and the external excitation, respectively.

The limit state function in a structure can be a criterion which controls the stress or displacement and etc. The external excitation can be any type of load such as dead load, live load, wind load, earthquake load, temperature change and etc. With the probability density functions of S and R being determined, reliability can be obtained from the following equation [16]:

$$R_e = \int dR_e = \int_{-\infty}^{+\infty} f_S(s)\left[\int_s^{\infty} f_R(r)dr\right] ds \quad (3)$$

Where $f_R(r)$ and $f_S(s)$ are the probability density function of the system and the external excitation, respectively. The more the probability density functions of R and S overlap, the lower the reliability of the system is. One of the problems in calculating the reliability of a system is determining the limit state function because in most cases it cannot be obtained definitively and analytically. Classic analytical methods such as First Order Reliability Method or Second Order Reliability Method are suitable to calculate the reliability of small and medium sized structures but for a large grid like a space structure with nonlinear behavior, these methods face serious difficulties [10]. In such cases, simulation is the only tool with which to calculate reliability. In the Monte Carlo simulation method, after verifying the deterministic and probabilistic variables and the limit state function of the system, a long sequence of random number will be generated for them based on the probability density function of the variables. Generating these numbers is quite an easy task using the OpenSees software. For every set of random numbers, the limit function of the system will be obtained. If LSF≤0, it means that failure has taken place in the system and if LSF>0, it denotes the performance of the system. Finally, for a large number of samples the following can be written:

$$R_e = n/N \quad (4)$$

Where n and N are the number of instances when the system has a desirable performance and the total number of cases, respectively. In practice, by creating a narrow range of numbers the failure probability will be obtained. Therefore, the calculated failure probability would only be an estimation of the structure’s real failure probability. Surely the accuracy of this estimation would get closer to reality if the numbers of simulations are increased. Despite the fact that this method is rather costly and time consuming and with the computing capacity of digital computers rapidly increasing, it is widely employed in engineering problems because of its unique features and capabilities [18].

3. Analytical model

In this study, the most widely used configuration of flat double-layer grids, meaning the square upon square type, has been employed. Three flat double-layer grids with 2, 3 and 4 meter members have been modeled. The dimensions of the plan of the studied grids were considered 24 m×24 m. Also, the space between the two layers was considered 2 meters and the grids with 2, 3 and 4 meter members are composed of 1152, 512 and 288 members, respectively. Three types of supports have been considered: Corner supports (A), Edge supports (B) and surrounding supports (C). Also, all the supports are hinges. The configurations of the studied structures are provided in Figures 1, 2 and 3. All the members of the structures are pipes. The yield stress and the modulus of elasticity of the steel are considered to be equal to 360 and 210000 MPa, respectively.

The structures were designed when being subjected to 50 Kg/m^2 of dead, cover and connection loads and 200 Kg/m^2 of snow load [9]. The uniformly distributed load was cross multiplied by the load bearing area of each joint of the upper layer and was applied to them as concentrated loads. Also, the four diagonal corner members of the structure were considered as solid circular rods and so the local failure in these members was prevented. The structures were designed using the load and resistance factor design, in accordance with the AISC-LRFD99 guideline [1] and based on the least weight optimization; the sections presented in Table 1 were obtained for the members.

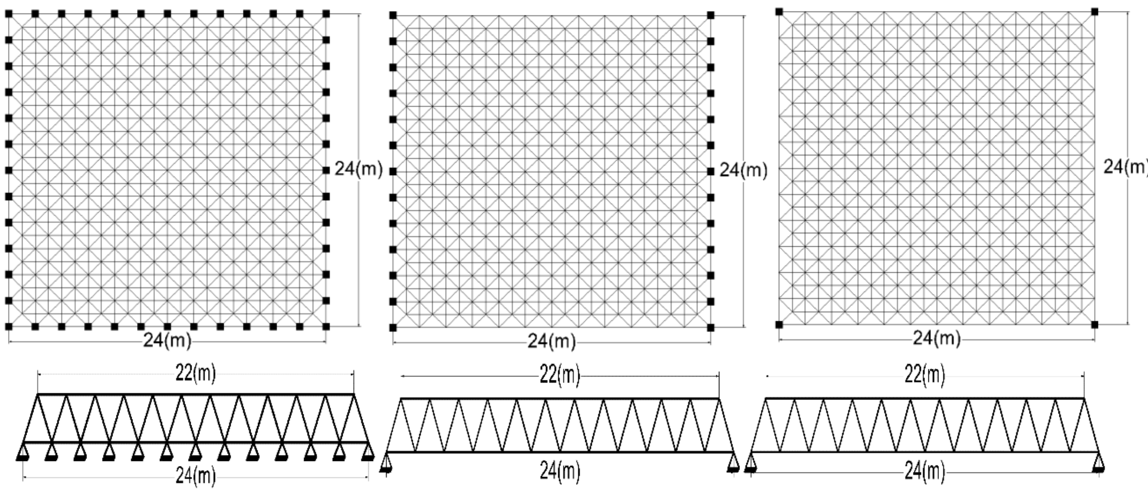
Table 1. Member size of model grid structures

Kind of Supports	Horizontal Members Length	Sections (mm)
Corner	2 meters (12*12 bay)	CHS 88.9*12
		CHS 120*8
	3 meters (8*8 bay)	CHS 114.3*8
		CHS 130*10
	4 meters (6*6 bay)	CHS 133* 6
		CHS 140*12
Edge	2 meters (12*12 bay)	CHS 60.3*12
		CHS 130*6.3
	3 meters (8*8 bay)	CHS 88.9*10
		CHS 160*10
	4 meters (6*6 bay)	CHS 108*8
		CHS 160*12
Surrounding	2 meters (12*12 bay)	CHS114.3x10
		CHS48.3x6.3
	3 meters (8*8 bay)	CHS139.7x8
		CHS68.9x10
	4 meters (6*6 bay)	CHS163.8x8
		CHS88.9x12

4. Modeling the nonlinear behavior of compressive members

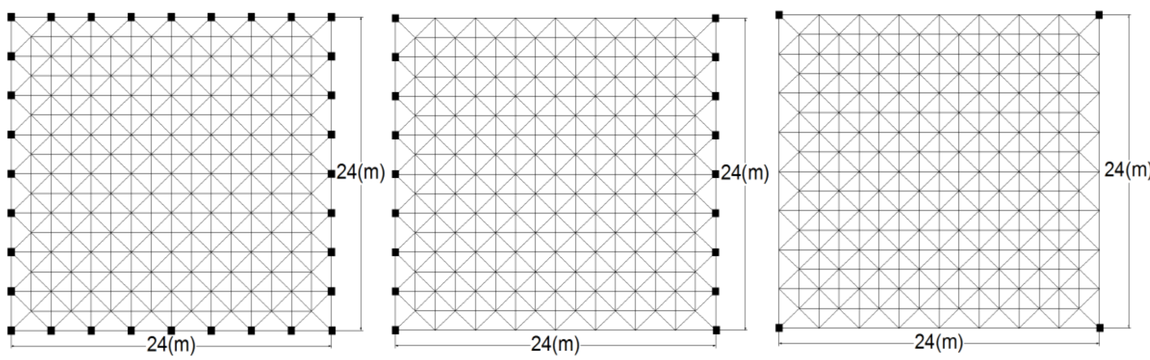
Length imperfections cause initial deformation and stress in a structure. Different methods can be used to investigate the effect of this type of imperfection on a structure. Methods such as the virtual work method, compatibility of deformations, concept of energy, and Koiter's theory of stability necessitate the solving of complex equations; thus, employing them for complex structures such as space trusses is not possible. One suitable method to investigate the effects of these types of imperfections is nonlinear finite element analysis.

The behavior of compression members has a significant effect on the failure mechanism of double-layer space structures. Nearly all members of a double-layer grid structure primarily carry axial forces. When a tension member reaches its yield point, its stiffness decreases to zero and this state continues until strain-hardening occurs. When a compression member buckles under compression forces, it might not be able to carry additional loads. As the member continues to shorten, the axial force must also decrease to maintain balance. When applied load exceeds the elastic limit of the structure, buckling of some compression members will cause a sudden reduction in load-carrying capacity of the whole structure and redistribute the internal forces. If the structure can tolerate this redistribution, it might be able to carry additional loads, otherwise other members will fail and progressive collapse of the system is possible.



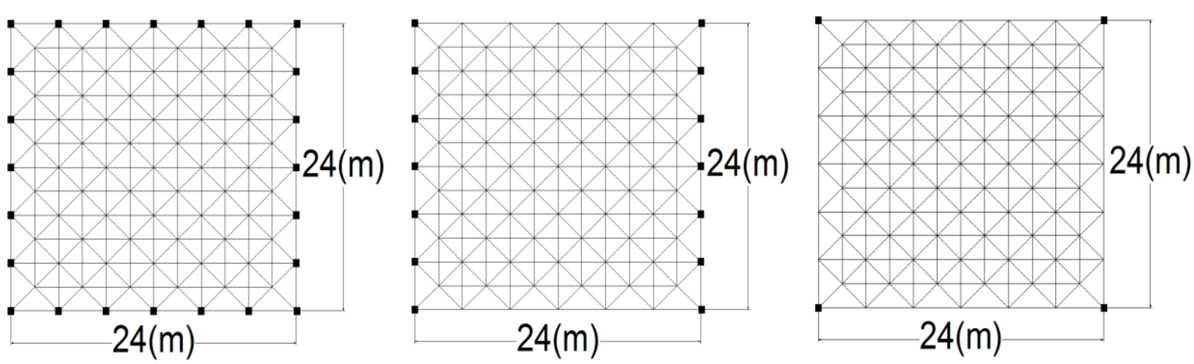
(A): GC12 (B): GB12 (C):GA12

Figure 1. Configuration of the double layer grids for 2 meters horizontal members' length (12*12 bay)



(A): GC8 (B): GB8 (C):GA8

Figure 2. Configuration of the double layer grids for 3 meters horizontal members' length (8*8 bay)



(A):GC6 (B): GB6 (C):GA6

Figure 3. Configuration of the double layer grids for 4 meters horizontal members' length (6*6 bay)

The behavior of a simple pin-ended compression member is a function of the slenderness ratio, yield stress of the material, and initial imperfection of the member. This member may exhibit brittle or ductile behavior based on the variation in these three factors. Figure 4 shows a truss member with initial curvature imperfection that exhibits random buckling behavior. It was assumed that the curvature imperfection was in the shape of a sinusoidal half-wave along the length. The maximum initial deviation of the member in its mid-point is denoted by e. This member was created in OpenSees with 20 elastic perfectly-plastic non-linear displacement-based beam-column elements of equal length integrated at 4 points along the element. The integration was based on the Gauss-Legendre quadrature rule, which enforces Bernoulli beam assumptions. This section was captured with the fiber section element class in OpenSees that divided the whole section into 16 subdivisions (fibers) in the circumferential direction and 4 subdivisions in the radial direction (Figure 4). The axial force-displacement relationship of the model was obtained through displacement control analysis using the arc-length algorithm considering both geometric and material non-linearity.

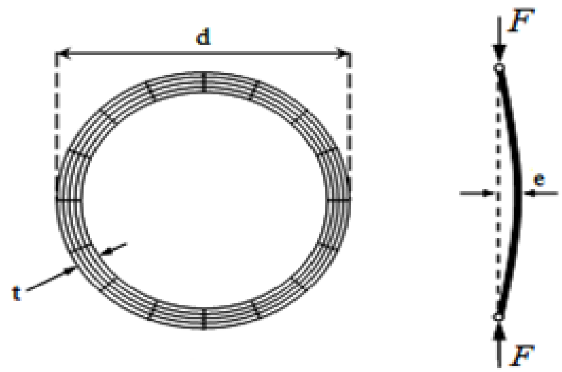


Figure 4. Geometrical and meshing specifications of the compression member model

To simulate the initial curvature imperfection, it is randomly assumed that the amount of this imperfection at the mid-span of the column, i.e. e, conforms to the Gamma probability distribution. The parameters of the Gamma distribution are chosen in such a way so that the mean of this value (e) would be equal to 0.001 of the member's length which is the permissible amount for this imperfection in this type of structural member. Also, the maximum amount of the imperfection is limited to 0.01 of the member's length and that's because it's quite easy to avoid using members with sizable amount of curvature. So, by generating random numbers through the Gamma distribution and the above said specifications, the probability density function of this imperfection was created. In this paper, three different lengths have been employed in the double-layer grid and each structure contains members with different lengths which have to be separately applied the curvature imperfection. As an example, the probability density function for member with the length of 2 meters is shown in Figure 5.

Afterwards, for each of the imperfections, a nonlinear analysis has been carried out and the load or the maximum force that the member can bear is calculated. In Figure 6, the load-displacement diagrams for each one of the imperfections in a 2 meter member are depicted. This Figure has been drawn based on the corresponding stresses and strains.

With this method, the compressive behavior of every imperfect member for different amounts of imperfection is determined and thenceforth by employing the multilinear approach, as demonstrated in Figure 7, the ideal stress-axial strain relationship is obtained. These diagrams have been used in the nonlinear push down analysis of the structure by reapplying the random length imperfection as the stress-strain behavior of the imperfect material. Videlicet, in lieu of applying the imperfection in the geometry of the model, the structure is modeled without any imperfection and the effect of the imperfection is accounted for in the stress-strain behavior of each member. In which case, the stress-strain diagram varies from one member to another as a consequence of the imperfection's random nature. As an example in Figure 7, the ideal stress-strain relationship of a 2 meter member in its imperfect state, with the cross section of 88.9*12 millimeters and the initial curvature of 4.5 mm, has been shown.

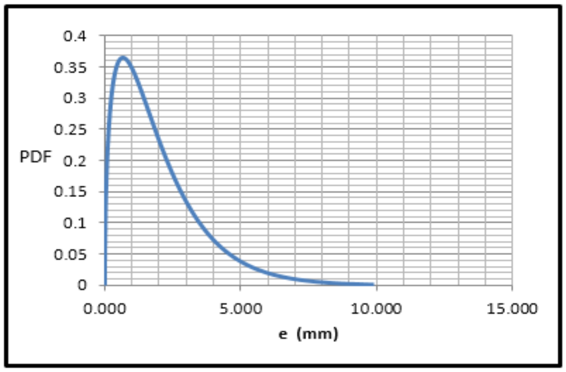
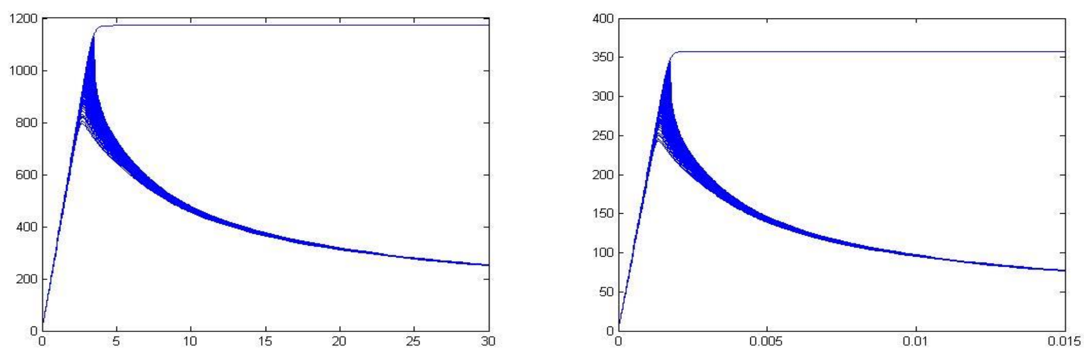


Figure 5. probability density function with gamma distribution as a sample for L=2m



(a) (b)

Figure 6. Relevant (a) axial force-displacement (b) stress- strain for compressive member with geometrical imperfections for 2 meters length members

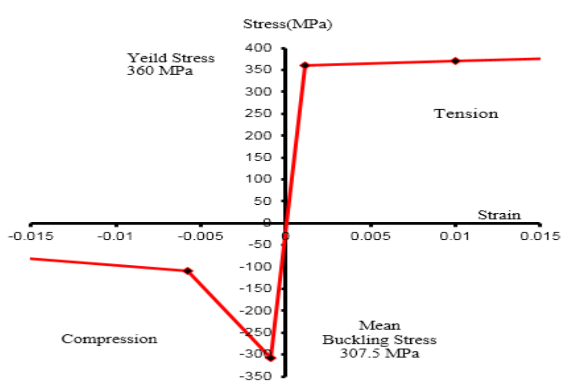


Figure 7. Axial stress-strain relationship for imperfect members L=2 m

5. Modeling of random imperfections in member length

Member length imperfections were also considered using normal distribution. The parameters of the normal distribution had an average of zero and a standard deviation of 0.0001 L (L = member length). The maximum imperfection was limited to 1% of the member length because application of members with large imperfections can easily be avoided. Member length imperfections for both long and short members were randomly taken into account according to the randomly generated numbers. These random numbers were generated using a normal distribution and the aforementioned specifications to obtain the PDF of the imperfections shown in Figure 8.

The method proposed by El-Sheikh was employed to model length imperfections of the members [5]. Figure 9 shows that, for a member to be in its ideal place, it must be subjected to tension or compression. These forces change the behavior of the member and also change the stress-strain diagram of the imperfect member. The length imperfections shown in Figure 9 have been exerted as force couples on the ends of the members to place them in position by lengthening or shortening them. The force exerted on the member to cause a change in length is:

$$P=E.A.\Delta L/L \quad (5)$$

where P, E, A and ΔL are the force applied to the member, the modulus of elasticity, the member's cross sectional area and the member's length imperfection, respectively.

Evidently these forces affect the stress-strain specifications of the member and to change the length of the member by the amount of $\pm\Delta L$, a force couple is needed to develop an axial stress equal to $\sigma = \varepsilon E = E\,\Delta L/L$. So, each of the ΔLs generated by the Gaussian distribution, correspond to the much applied forces that ultimately appear in the ideal stress-strain diagram of the imperfect member. In Figure 10 displays the stress-strain diagram of a 2 meter member with the cross section of 88.9*12 millimeters with the imperfection having been considered. As it was stated, the amount of the length imperfection of the members is random and obeys the Gaussian probability distribution. In this Figure, as an example, the values 1.7 and 2.3 millimeters are considered as the shortening and elongation of the member, respectively. It has to be mentioned that in this research, for every one of the length imperfections, this calculation has been performed and the stress-strain specifications of the imperfect member has been obtained similar to Figure 10. Therefore, diagrams like Figure 10 contain the simultaneous effects of both the initial curvature and length imperfections. Each of these stress-strain specifications are then randomly considered as the behavior of the imperfect material and modeled in the OpenSees software. It is worth mentioning that the structure has been nonlinearly analyzed thousands of times and for each analysis, equal to the number of the grid's members, stress-strain diagrams have been randomly produced for imperfect members.

6. Push- down analysis of the imperfect grids

To compute the bearing capacity of the imperfect grid, the initial curvature was considered as a random variable with a gamma distribution. Using nonlinear analysis, a stress-strain diagram was then obtained for each cross-length section. Allocating a random length imperfection to each member changes its ideal stress-strain diagram and the simultaneous effects of length imperfection and curvature of the member are incorporated by modifying the stress-strain diagrams. After allotting the stress-strain diagram of the imperfect material to each member, the structure was analyzed with the Push Down analysis along the vertical direction. The random allocation of imperfections and the nonlinear Push Down analysis were repeated thousands of times. In these analyzes, both the material and geometrical nonlinearities were accounted for and the diagram of vertical load applied to the structure against the vertical displacement of the mid joint of the lower layer was derived. The obtained results from 1000 simulations are presented as load-displacement diagrams in Figure 11. In these diagrams, the vertical and the horizontal axes represent force and displacement in terms of KN and millimeters, respectively.

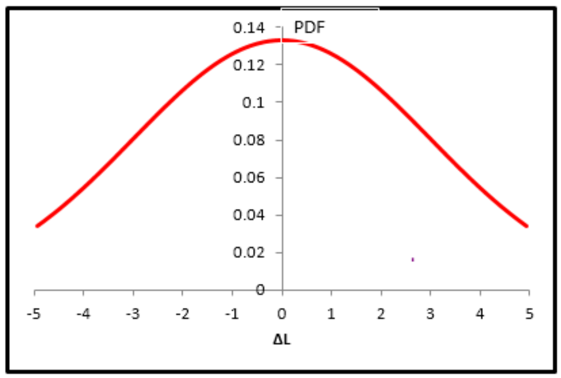
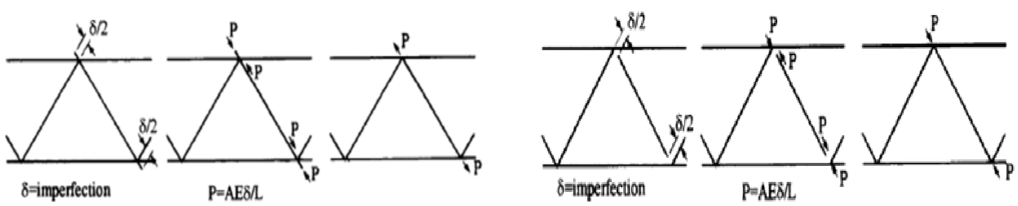
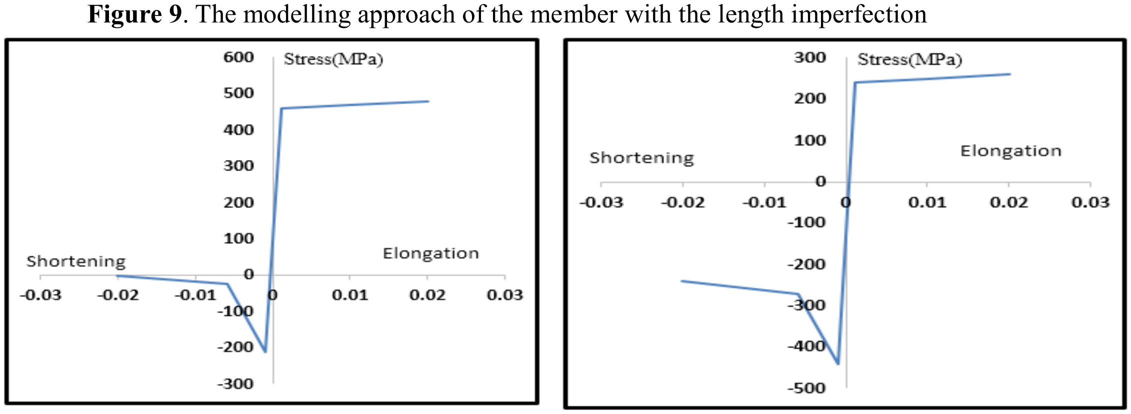


Figure 8. Probability density function of the members' length imperfections in compression members with normal distribution for 2 meter members



(a) long member (b) Short member

Figure 9. The modelling approach of the member with the length imperfection



(a) along member with ΔL=+2.3 (b) a short member with ΔL=-1.7

Figure 10. Idealized stress-strain relationship of imperfect members under tension and Compression for the 88.9*12(mm) sample with 2 meter length

If the first maximum points in Figure 11 are considered as the collapse and capacity points of the structures, the statistical distribution of the collapse load and the respective statistical parameters can be achieved. As an example and similar to Figure 12, the probability density function of the ultimate capacity of these systems for a 2 meter flat grid with corner supports are obtained. The statistical specifications include the average value, standard deviation of the collapse load of the studied systems are also provided in Table 2. Moreover, in this table, the minimum and maximum capacities during 1000 random analyzes of the structures are presented.

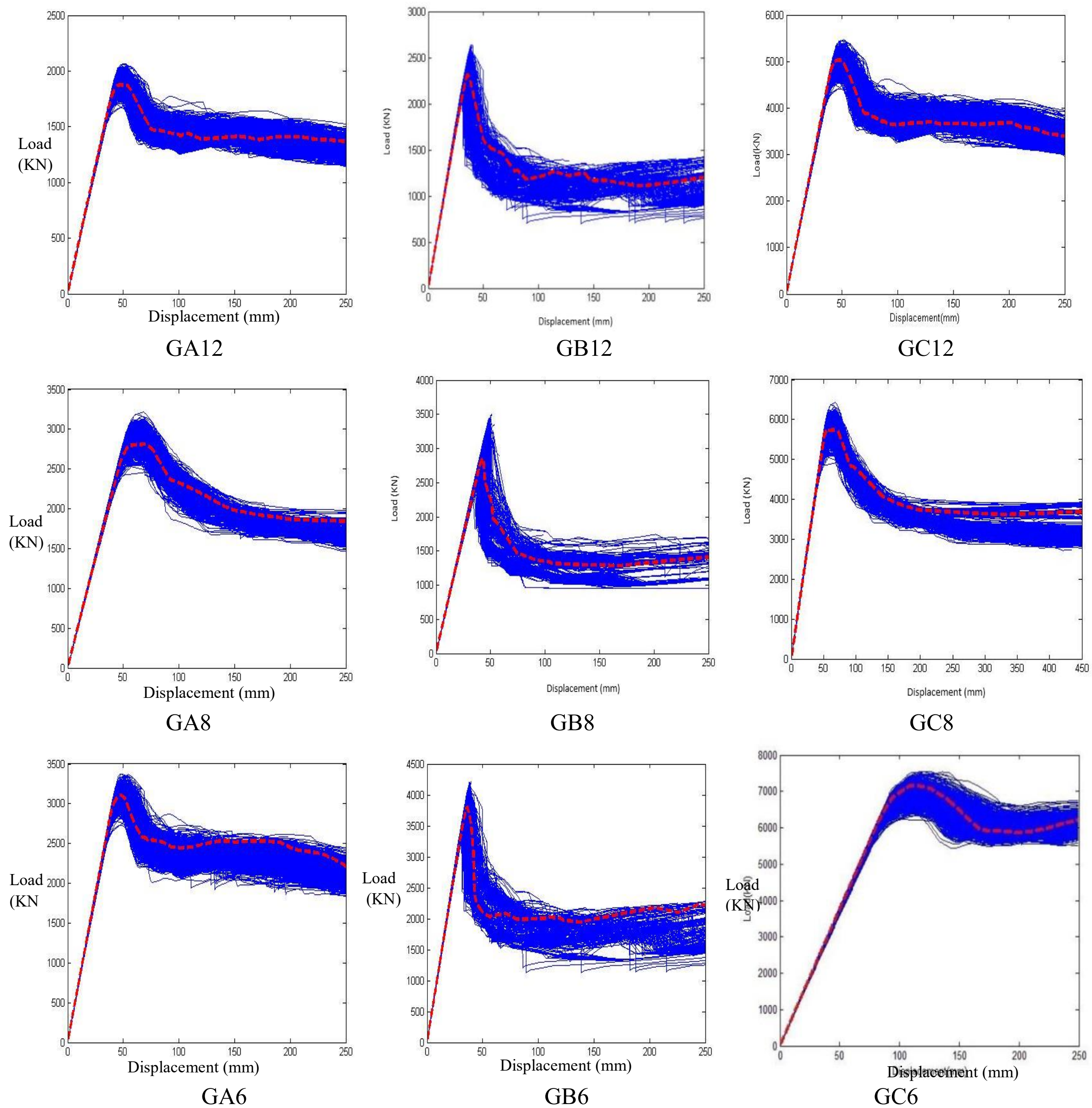


Figure 11. Load-displacement diagrams of the double-layer space structures

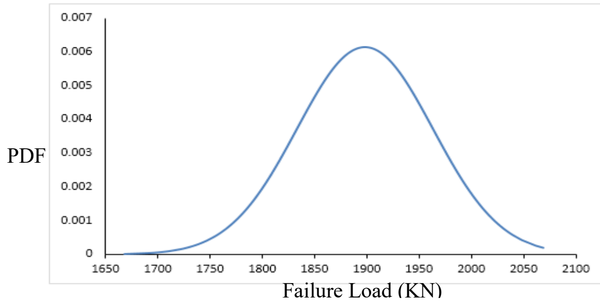


Figure 12. Probability density diagram of the collapse load for 2 meter flat grid with corner supports

Table 2. Statistical specifications of the collapse load

Grids Name	Failure Load (KN)				
	μ_p	σ_p	p_{max}	p_{min}	(CV) %
GA12	1899	65	2068	1667	3.42
GB12	2375	101	2640	1911	4.25
GC12	5023.5	172	5470	4410	3.24
GA8	2886	109	3216	2481	3.77
GB8	2980	201	3507	2279	6.74
GC8	5771	218	6433	4962	3.78
GA6	3111	106	3375	2724	3.40
GB6	3751	171	4325	3221	4.55
GC6	6941	208	7553	6233	2.99

μ_p (Average), σ_p (Standard Deviation), CV(the coefficient of variation)

As it can be seen, by increasing the number of supports, the load bearing capacity of the structures heightens and structures with surrounding supports have a much higher capacity compared to the ones with corner and edge supports and when a member of the structure fails, the drop in the capacity of the system is quite low.

7. Result and discussion

Structural reliability is the probability of a system's desirable performance. That is to say a structure has to desirably and without failure carry out the intended obligations during its life span. The reliability of a system, Re, is defined in terms of the system's failure probability, P_f, and is expressed as $R_e=1-P_f$. A system's reliability at a specific load such as F_s, is equal to the probability that the collapse load or the capacity of a system, F, being greater than the mentioned value. This definition can be express within the following mathematical from:

$$R(F_s)=P(F>F_s) \qquad (6)$$

Considering the calculated failure probability distributions and by using equation (6), the reliability of flat double-layer systems can be obtained similar to Figure 13 in which the reliability of a 2 meter flat double-layer space grid with corner supports has been determined. It has to be pointed out that the phrase "perfect structure" denotes an ideal structure with no imperfections for which the highest ultimate capacity has been achieved. Since constructing the perfect structure is practically impossible, the structure which has displayed the highest capacity during 1000 analyzes of random distribution of imperfections is considered as the perfect structure or the closest system to the perfect structure.

The reliability of 2, 3 and 4 meter flat double-layer grids with different supports are presented in Tables 3 through 5. The second column shows the capacity drop of the system due to the simultaneous existence of geometrical imperfections. In these Tables, in addition to the aforementioned information, another column has been added under the title "load increase factor". In order to achieve the intended safety, the designer of the structure has to multiply the required ultimate capacity of the system by the load increase factor from the last column of the Tables.

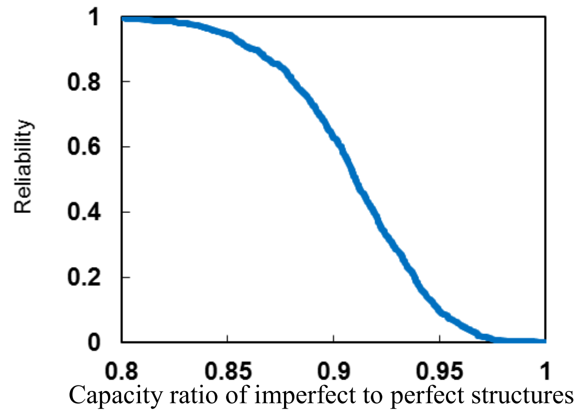


Figure 13. Reliability of the GA12 double-layer space structures

Table 3. Reliability of the G12 double-layer space structures

Reliability	capacity ratio of imperfect structure to perfect structure			Coefficient Load factor		
	GA12	GB12	GC12	GA12	GB12	GC12
1	0.842	0.800	0.890	1.16	1.20	1.11
0.99	0.851	0.811	0.889	1.15	1.19	1.11
0.98	0.861	0.822	0.895	1.14	1.18	1.11
0.97	0.870	0.836	0.899	1.13	1.17	1.10
0.96	0.883	0.840	0.902	1.12	1.16	1.10
0.95	0.886	0.852	0.904	1.12	1.15	1.10
0.94	0.888	0.858	0.906	1.11	1.14	1.09
0.93	0.890	0.861	0.908	1.11	1.14	1.09
0.92	0.891	0.863	0.910	1.11	1.14	1.09
0.91	0.893	0.866	0.911	1.11	1.13	1.09
0.9	0.894	0.868	0.912	1.11	1.13	1.09
0.85	0.901	0.877	0.918	1.10	1.12	1.08
0.8	0.906	0.885	0.922	1.09	1.12	1.08
0.75	0.910	0.891	0.926	1.09	1.11	1.07
0.7	0.921	0.910	0.939	1.08	1.09	1.06

Considering Figure 13 and Table 3, in a 2 meter flat grid with corner supports and in designing a system with the reliability of 0.99, it can be seen that the capacity of the imperfect system is equal to 85 percent of that of the perfect system which is 15 percent lower than the capacity of the ideal system. In other words, for designing a safe system with the reliability of 0.99, the designing capacity of the structure has to be considered 15 percent higher. Or, for example, that to design a system with the reliability of 0.95 it is seen that the capacity of the imperfect system is 0.88 of that of the perfect system which is 12 percent lower than the capacity of the ideal system. The results for other types of flat grids can be obtained from Tables 4 and 5.

Tables 3 through 5 can be interpreted in another way. Let’s assume a flat double-layer grid with the length of 2 meters and corner supports is to be designed (without considering the statistical and random nature of the discussed imperfections). In which case, if the desirable reliability is 0.98, the system's required ultimate capacity has to be multiplied by the load increase factor from the last column of Table 3, i.e. 1.11, so that the intended designing safety can be achieved. In addition to this, knowing the maximum bearable load by the structure provides the designer with the possibility to evaluate the safety of the structure against any possible amount of excessive load imposed on the structure and if necessary, adopt the appropriate measures to enhance the safety of the structure.

Table 4. Reliability of the G8 double-layer space structures

Reliability	capacity ratio of imperfect structure to perfect structure			Coefficient Load factor		
	GA8	GB8	GC8	GA8	GB8	GC8
1	0.772	0.741	0.851	1.23	1.26	1.15
0.99	0.780	0.755	0.857	1.22	1.25	1.14
0.98	0.800	0.759	0.861	1.20	1.24	1.14
0.97	0.811	0.768	0.865	1.19	1.23	1.14
0.96	0.823	0.773	0.869	1.18	1.23	1.13
0.95	0.831	0.780	0.872	1.17	1.22	1.13
0.94	0.840	0.783	0.874	1.16	1.22	1.13
0.93	0.843	0.788	0.876	1.16	1.21	1.12
0.92	0.846	0.792	0.878	1.15	1.20	1.12
0.91	0.849	0.811	0.880	1.15	1.19	1.12
0.9	0.850	0.823	0.881	1.15	1.18	1.12
0.85	0.859	0.834	0.888	1.14	1.17	1.11
0.8	0.867	0.840	0.894	1.13	1.16	1.10
0.75	0.883	0.852	0.911	1.12	1.15	1.09
0.7	0.891	0.863	0.922	1.11	1.14	1.08

Table 5. Reliability of the G6 double-layer space structures

Reliability	capacity ratio of imperfect structure to perfect structure			Coefficient Load factor		
	GA6	GB6	GC6	GA6	GB6	GC6
1	0.731	0.701	0.821	1.27	1.30	1.18
0.99	0.741	0.713	0.833	1.26	1.29	1.17
0.98	0.750	0.722	0.840	1.25	1.28	1.16
0.97	0.766	0.733	0.855	1.24	1.27	1.15
0.96	0.771	0.746	0.861	1.23	1.26	1.14
0.95	0.780	0.753	0.871	1.22	1.25	1.13
0.94	0.790	0.761	0.880	1.21	1.24	1.12
0.93	0.804	0.773	0.881	1.20	1.23	1.12
0.92	0.807	0.777	0.891	1.19	1.22	1.11
0.91	0.810	0.780	0.892	1.19	1.22	1.11
0.9	0.812	0.784	0.893	1.19	1.22	1.11
0.85	0.822	0.799	0.899	1.18	1.20	1.10
0.8	0.831	0.810	0.912	1.17	1.19	1.09
0.75	0.838	0.820	0.922	1.16	1.18	1.08
0.7	0.852	0.822	0.933	1.15	1.18	1.07

8. Conclusion

The existence of imperfections in double-layer space structures with hundreds of members and joints is inevitable. In this study, the simultaneous effects of random initial curvature and length imperfections on double layer flat grids have been investigated. The carried out investigations based on nonlinear finite element analyses in the OpenSees software and the Monte Carlo simulation method suggest the sensitivity and significant capacity drops of these structures due to random initial geometric imperfections. By deriving the reliability diagrams (such as the diagram shown in Figure 13 and the Tables 3, 4, and 5) and by employing them in the design of the structure, the necessary design load to achieve the required safety can be easily determined. As a matter of fact, possessing such diagrams helps the designer to conduct his designs with the intended level of safety and without the need to perform detailed reliability analyzes for every specific design.

Analysis of selected structures by using Monte Carlo simulation method indicates that these structures are highly sensitive to random imperfections. It is concluded that increasing the number of supports will results in increasing the load carrying capacity of the structures because of existing multiple alternative paths which the applied load can be redistributed in the structure. Therefore, system with surrounding supports show greater capacities than those in edge and corner supports.

As expected, as the bay numbers increased, the effect of the initial imperfection on double layer load carrying capacity decreased. This indicates that the use of more members of shorter length in flat double layer space structures increases the reliability.

By considering Tables 3, 4, and 5, GA and GC have more reliability ratio in comparison with GB which it shows that the better behavior cannot be taken with increasing the number of supports. Actually, behavior of flat double-layer space structures with corner or surrounding supports is similar to two-way slab behavior, but edge support's behavior is similar to one-way slab. Thus, collapse behavior of flat double-layer space structures is significantly affected by number and situation of supports.

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