Proceedings of the IASS 2024 Symposium
Redefining the Art of Structural Design
August 26-30, 2024, Zurich Switzerland
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Stability analysis of double layer grids equipped with accordion force limiting device

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Abstract

Space Structure is a popular structural form for covering large areas without intermediate columns. Space trusses has tendency to collapse in brittle manner because of compression member's failure. Buckling compression members in space structures may lead to progressive collapse. Collapse of these structures could cause severe economic loss as well as life loss. In order to modify the behavior of space structures, Accordion force limiting device used to develop double layer grid's behavior. Numerical models were developed to investigate the effect of applying AFLD to double layer grids stability. A parametric study carried out to provide better insight into effect of AFLD according to support conditions as well as geometric proportions of double layer grids. Results indicate that applying AFLDs increase load carrying capacity in all models. It also prevents models from progressive collapse.

Keywords: Accordion force limiting device, Double layer grid, Stability analysis, Progressive collapse.

1. Introduction

Space structures are the best solution for covering large areas without intermediate columns. The most significant feature of these structures is their delicate appearance, ease of erection, light weight as well as being economic, Nooshin [1]. Despite these valuable advantages, some space structures are vulnerable to progressive collapse depending on their structural configuration, boundary conditions, applied loading as well as loss of key members. Progressive collapse mostly commences due to buckling of compression members which often possess brittle buckling behavior, (Schmidt et al. [2], Thornton and Lew [3]). Space structures are mostly used as roofing system for overcrowded sites such as airports and gyms; therefore, their collapse can lead to great loss of lives and property. Accordingly, a variety of mechanisms have been developed over the years to prevent the progressive collapse and improve the double layer space structure's response. These mechanisms can be generally classified as force management and ductility management, Hanaor et al. [4]. Force management is based on controlling member's force distribution by appropriate design of geometric configuration. Diagonal member removal and utilizing eccentric diagonal members are the methods classified in this category. The basic idea behind the ductility management method is utilizing the reserve load carrying capacity inherent in ductile redundant systems. Two main methods in this category are under-designing the critical tension members and utilizing FLDs. Among the aforementioned methods, FLD is an effective tool for preventing the sudden buckling of compressive members, due to its dominant capability in obtaining constant load carrying capacity regardless of the influence of imperfections (Tada et al. [5] and Schmidt et al. [6]). The basic idea behind this mechanism is applying FLD to critical compression members in order to modify the brittle post-buckling behavior of compressive members into the elastic-perfect plastic behavior ith long plateau of member ductility, as shown in Figure1.

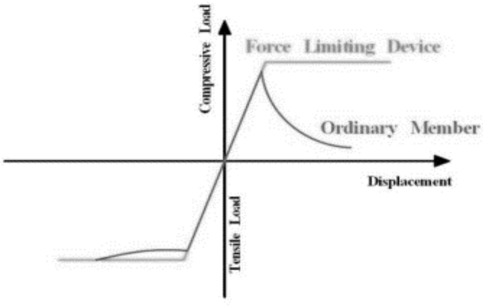


Figure 1: FLD's behavior in comparison with behavior of ordinary members

The initial concept of FLD for preventing progressive collapse was presented, Schmidt et al. [6]. The FLD was used for obtaining constant load carrying capacity in double layer space structures. In a subsequent work, Hanaor et al. [7], introduced two distinct types of FLD; hydraulic cylinder FLD and friction FLD. In the former, a hydraulic piston was included in the FLD which operated by exceeding the fixed pressure. The friction FLD which operated by moving a metal rod through a cutting tool, indicated better force-displacement behavior although it was complicated to obtain fixed limit load for this case. The multi-tubular FLD was introduced by Parke [8]. This FLD was consisted of two square hollow section tubes and four rectangular strips. The characteristics of this FLD were found to be dependent upon length and cross sectional area of the strips. This experimental work demonstrated that the multi tubular idea could efficiently improve the ductility of double layer grid space trusses, though it did not significantly recover the elastic force distribution inside grid. Mukai et al. [9] experimentally inserted the multi tubular FLD to three small scaled grids. Their results showed that multi tubular FLD is a good mechanism for improving the load capacity and deformability of truss structure provided that FLD be fitted to the members with the largest compressive axial force as well as the members with compressive axial force close to the largest one. Elsheikh [10], carried out a parametric study to investigate the effects of applying FLD on the behavior of double-layer trusses, considering different parameters such as truss configuration, aspect ratio and boundary conditions. Results indicated that effect of FLDs becomes more evident in corner supported space trusses. The applicability of FLD for handling the compression member buckling issue under transient wind load has been demonstrated in a numerical work by Bai et al. [11]. In this work, the Monte Carlo method combined with response surface approach was adopted to consider uncertainties related to wind load change rate and member imperfections under combined static and transient wind loading. It was observed that utilization of FLDs was helpful in reducing the failure probability of roof collapse under transient wind load. Subsequently, Bai et al. [12], studied nonlinear Dynamic behavior of steel roofs equipped with FLDs under transient up-lift wind pressure and showed that applying FLDs significantly reduces structure's deformation under upward wind load. In a more recent work, Shekastehband [13], numerically investigated in to the effect of applying forcé limiting device on tensegrity space structures behavior. Results indicated that applying FLD to a small selection of members considerably improves the load carrying capacity and initial stiffness. It was also found that the effect of applying FLD becomes more noticeable as the number of supports decreases. The mentioned sophisticated versions of FLD are now available in the technical literature, each having its own cons and pros. Ineffective control of the force-displacement characteristics, is considered as the significant drawback of the aforementioned FLD versions. To this should be added the fact that they are not able in obtaining the ultimate load carrying capacity as well as achieving the elastic-perfect plastic behavior. Poursharifi et al. [14], introduced a new generation of FLDs inspired by buckling restrained braces which is called Accordion force limiting device.

2. Introducing Accordion force limiting device

Accordion Force limiting devic is a newly developed generation of common FLDs [14]. In comparison with ordinary FLDs, AFLD has enhanced characteristics in terms of force carrying capacity and ductility as well as providing constant load level. The most important feature of this soft member is that encasing acts as restraining system preventing the core from buckling. It is worth mentioning that, AFLD can be installed in double layer space trusses like the ordinary members and is compatible with all joint types. Being inspired by BRB configuration, AFLD is consisted of three main parts including cylindrical core, tubular encasing and joint system as shown schematically in Fig. 2.

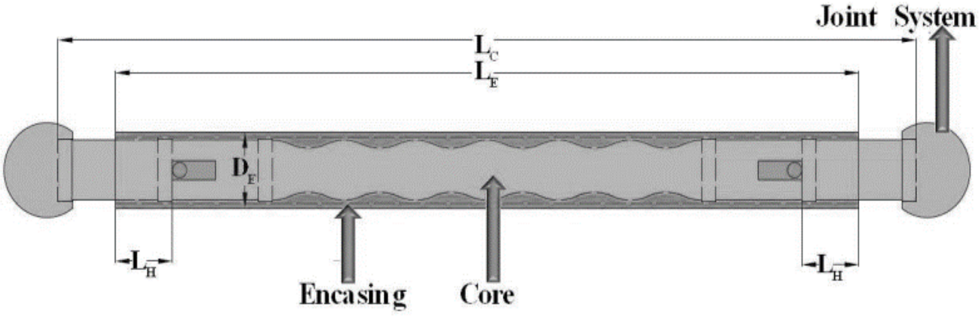


Figure 2: Schematic figure of AFLD [14]

It is to be mentioned that the cylindrical core is not tubular and it is a solid shaft. As seen in this figure, the accordion shape core with length of *Lc* is located inside a tubular encasing with length of *LE* and diameter of *DE*. Two joints are placed at the two ends of core. Two assembling holes are drilled in a finite distance (*LH*) from two ends of encasing to fix the core location inside the encasing. Slotted holes are considered to enable the free movement of core during the compression test. Bolt connection is used to connect encasing to core as well as spherical joint to core. By using bolt connections, AFLD can be assembled fast and disassembled easily. Furthermore, even after buckling of core, encasing can be used in other AFLDs. In the present study critical compression members are substituted with AFLD. Two tests were carried out to investigate AFLD's behavior under uniaxial compressive loading. Two experimental tests carried out by autor to investigate AFLDs behavior. AFLD was loaded in compression according figure 3.

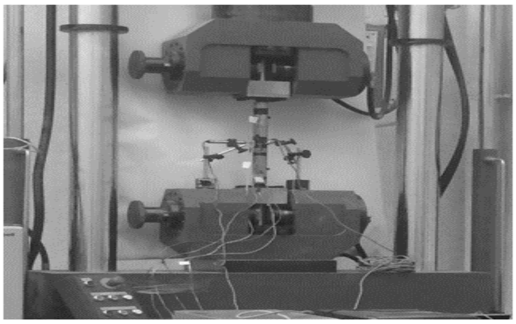
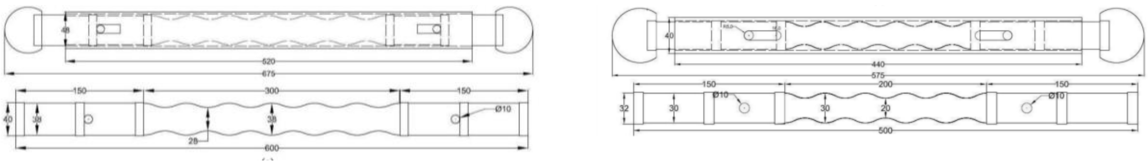


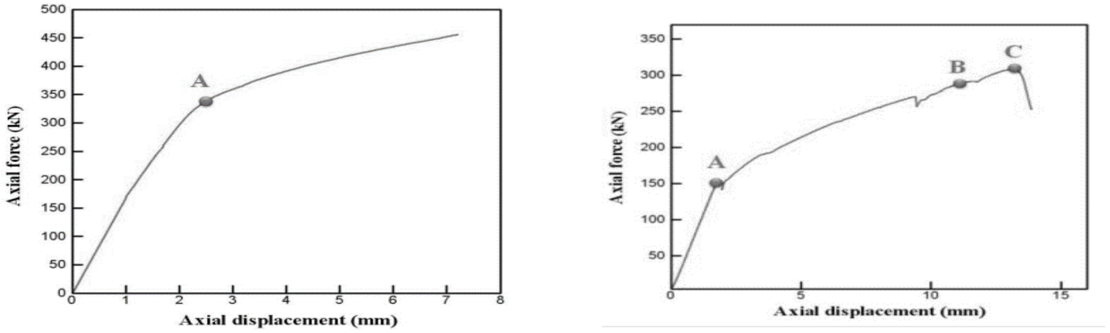
Figure 3: Experimental test setup [14]

Detailings of specimen 1 and 2 are shown in figure 4. the axial force-axial displacement response was recorded by UTM. Figure 5 shows the axial force-axial displacement response of the first test specimen



(a) (b)

Figure 4: Detailing of AFLD design (Unit: mm): (a) Test 1, (b) Test 2 [14]



A) Test 1 B) Test 2

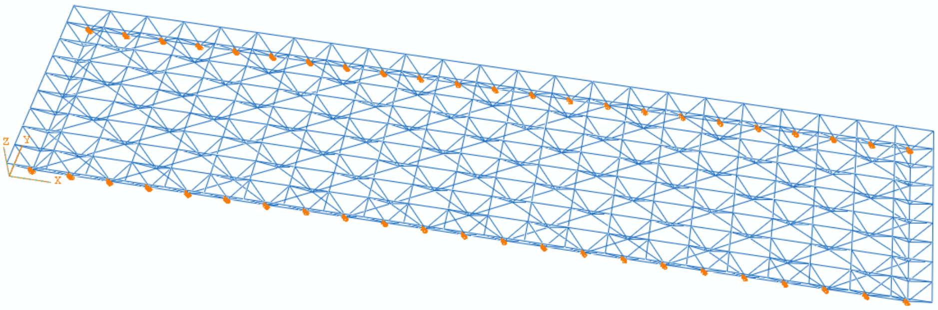
Figure 5: The axial force-axial displacement response of test 1 and test 2 [14]

Since for the case of first specimen, the adequate force could not be provided by UTM, the second test specimen (the specimen with dimensions shown in Fig. 4-b) was performed. The second test specimen which was more slender in comparison with the first specimen, enabled the test procedure to proceed towards the collapse step. The axial force-axial displacement response of second test specimen is illustrated in Fig. 5-b. This figure shows that yielding started to occur at the axial load level of approximately 140 kN as pointed by letter A in this figure. Then, AFLD continued to carry compression load followed by formation of extra plastic hinges. In point B, all plastic hinges were formed and AFLD reached its ultimate loading capacity. The constant loading plateau is obviously shown in Fig. 5-b. Subsequently, core met the encasing followed by increasing the load carrying capacity. The excessive strength caused by encasing’s confining effect on core is obviously visible in Fig. 5-b, as the curve continues its ascending path to reach point C. In this point, due to excessive lateral displacement, encasing began to show out of plane buckling and the specimen started to collapse. In this point, excessive lateral force exerted by core led to encasing’s global buckling.

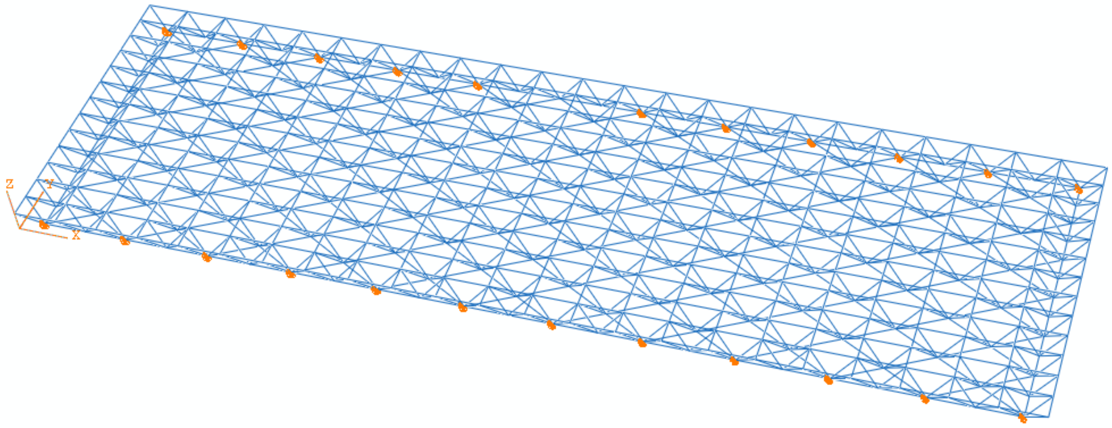
3. Design and analysis of double layer grids

3.1. Design of double layer grids

The present parametric study involves six models of double layer grids equipped and not equipped with AFLD. All the models have square on square configuration. Two of models in ABAQUS finite element software are shown in figure 6. Properties of models are mentioned in table 1. Configuration of all models is binate on larger obnate pattern. Models are developed in Formian software. Then transferred to SAP 2000 to design considering wind, snow, dead, earthquake, rain, roof live and temperature loads according to Iran’s code for steel structures using LRFD method. The member sections were selected pipe type as usual space structures members. The slenderness ratio of all members are limited to 100 according to Iran’s code for space structures.



A) Model 1



B) Model 6

Figure 6: Configuration of model 1 and model 6

Table 1. Properties of models

Model Number	Length (m)	Span (m)	Depth (m)	Support Distance	Aspect Ratio	Loading Pattern
1	96	24	2	4	4	symmetric
2	96	24	2	8	4	symmetric
3	96	24	2	12	4	symmetric
4	96	12	2	8	8	symmetric
5	96	18	2	8	5.3	symmetric
6	96	30	2	8	3.2	symmetric

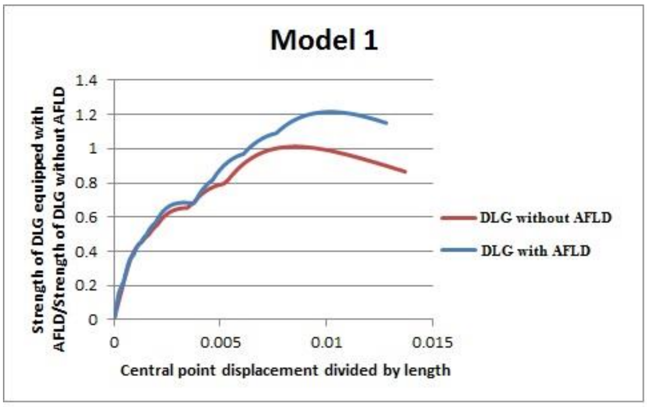
3.2. Stability analysis of double layer grids

Finally models are transferred to ABAQUS finite element software. All the Double layer grids members are modeled in ABAQUS software applying B32H element. Material is assumed to be elastic-perfect Plastic ST37. Imperfection of L/1000 applied in the middle of member. Member behavior is assigned to double layer grids and static riks analysis is carried out. First of all models are subjected to gravity loads. Then critical members are distinguished and substituted by AFLD. Critical members usually occur near supports. In order to investigate AFLDs effect on stability of double layer grids, risk analysis carried out on models equipped with AFLD.

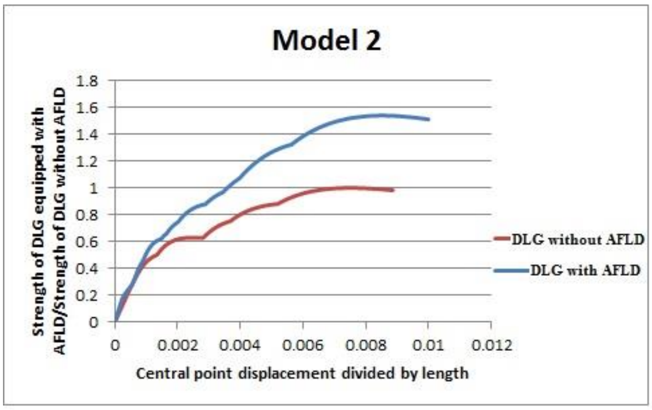
4. Results

4.1 Support distance

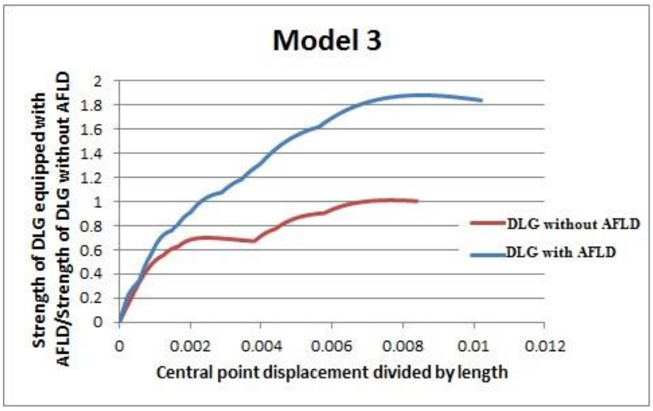
Three models with support distances of 4, 8 and 12 meters are developed to investigate effect of applying AFLD on stability of double layer grids with different support distances with symmetric loading (models 1 to 3 in table 1). The results are shown in figure 7. In the following results, vertical axis indicates strength of double layer grid equipped with AFLD divided by strength of same double layer grid without AFLDs. Horizontal axis shows double layer grids central point displacement divided by length of double layer grid.



A) Model 1



B) Model 2

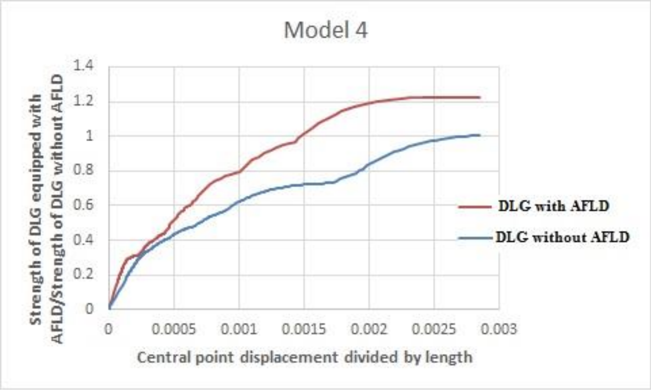


C) Model 3

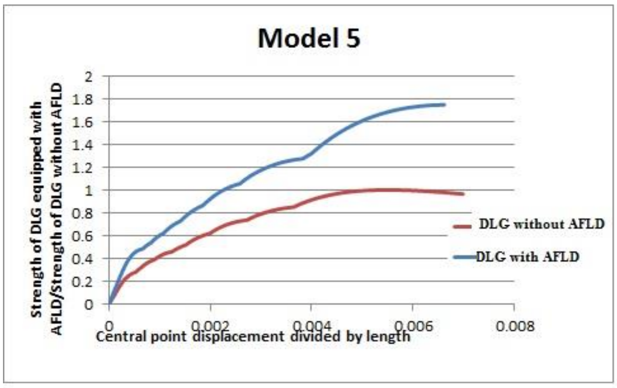
Figure 7: Load-displacement behavior of Double layer grids equipped with AFLD with different loading patterns and support distances

4.2 Aspect ratio

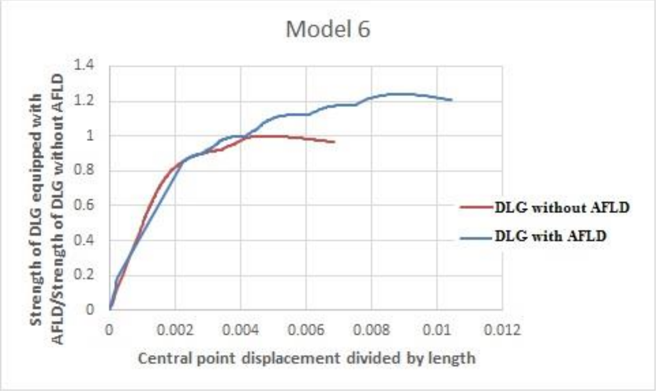
three models with different length to span ratios (aspect ratio) are developed to investigate the effects of applying AFLD, considering symmetric loadings (models 7 to 9 in Table 1). The results are shown in figure 8.



A) Model 4



B) Model 5



C) Model 6

Figure 8: Load-displacement behavior of Double layer grids equipped with AFLD with different aspect ratios

5. Conclusion

Accordion force limiting device is an innovative device which is designed based on buckling restrained brace. This device is applied to critical compression members in order to prevent them from buckling. Critical members usually occur in web members around supports and in the middle of grid on top layer. In all models approximately 10% of members substituted by AFLD. By increasing support distance, effect of AFLD becomes more signifant. Results indicate that in all models regardless of aspect ratio and support distance, applying AFLD leads to higher stability and load carrying capacity of double layer grids. Load carrying capacity improves 20% to 80% by adding AFLD to models.

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