Effect of Accordion Force Limiting Device on Double Layer Barrel Vaults Seismic Behavior

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Abstract

Space structures are best solutions to cover large areas without intermediate columns. These structures benefit light weight, ease of erection as well as mass production. The most significant defect of space structures is progressive collapse. Progressive collapse mostly occur due to brittle failure of compressive members. Accordion force limiting device which is an innovative soft member is used in order to modify space structures behaviour and improve their stability. Accordion force limiting device designed based on buckling restrained braces and accordion metallic damper. Experiment tests on two all steel accordion force limiting devices reveal that it alters space structure member's brittle post buckling behaviour into elastic-perfectly plastic behaviour. In this study seismic behaviour of double layer barrel vaults equipped with accordion force limiting device due to vertical and horiontal components of earthquake motion is investigated. A Parametric study is carried out to cover Rise to span ratio related to double layer barrel vaults configuratio. Also three earthquake records are chosen to be applied to models. Results indicate that applying AFLD to all models improve their seismic behaviour.

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.

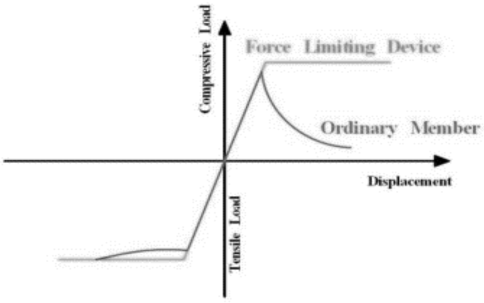


Figure 1: FLD’s behavior in comparison with behavior of ordinary members

The initial concept of FLD for preventing progressive collapse was presented by 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 force 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.

As in this paper seismic behavior of double layer barrel vaults is going to investigate, a brief literature review of this issue is also presented in this part. The Kobe earthquake showed that although the vulnerability of the space structures is not as high as ordinary buildings, they are not aseismic (Cunieda

[15] and Ihsikawa et al. [16]). Saka et al. [17] revealed that the joints and the characteristic slender form of the frames have significant effect on the collapse of double layer grids. Kave [18] studied the effect of the geometric dimensions of the double layer barrel vaults and showed that any increase in the rise-to-span ratio of these structures may make their first-mode period to increase. Mogaddam [19], worked on a number of double layer barrel vaults with different configurations and various kinds of support conditions and concluded that the configuration of the barrel vaults significantly affect their first-mode period. However, the configuration showed no meaningful effect on the double layer barrel vaults seismic response. Sadeghi [20], studied the nonlinear dynamic behavior of a number of double layer barrel vaults and proposed a set of equivalent static earthquake loads for these structures and later tested these formulae. Results of analyses carried out over the structures shows that these formulae were considered in their design stage and also that their response were modified significantly in comparison with others designed without considering the suggested earthquake loads formulae (Sadeghi et al. [21]). Sadeghi [22] investigated the Simultaneous Effects of Horizontal and Vertical Components of Earthquakes on the Double Layer Barrel Vaults. Results indicate that in the stage of design to satisfy serviceability, it is enough to consider the horizontal component of the earthquake action on the structure. However, the limit state design, there is a need of consideration of both of the horizontal and vertical components of the earthquakes simultaneously.

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.

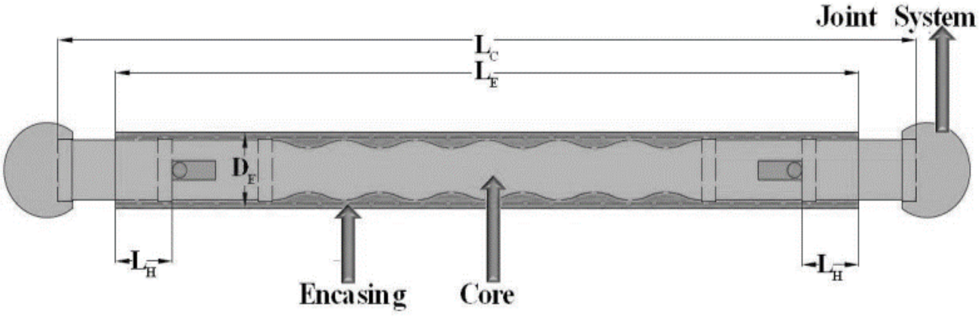


Figure 2: Schematic figure of AFLD [14]

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 L_c is located inside a tubular encasing with length of L_E and diameter of D_E. Two joints are placed at the two ends of core. Two assembling holes are drilled in a finite distance (L_H) 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. AFLD was loaded in compression according figure 3.

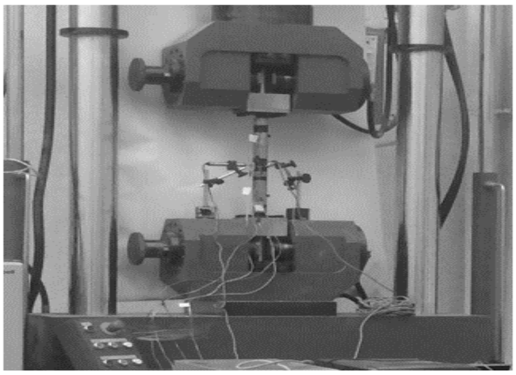
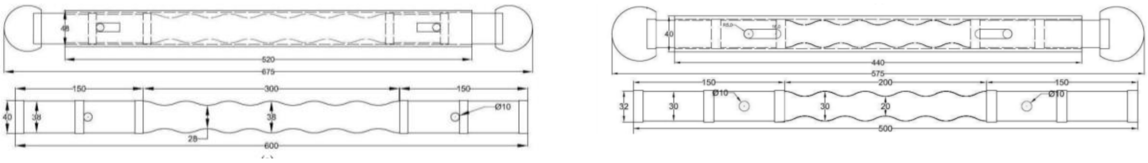


Figure 3: Experimental test setup [14]

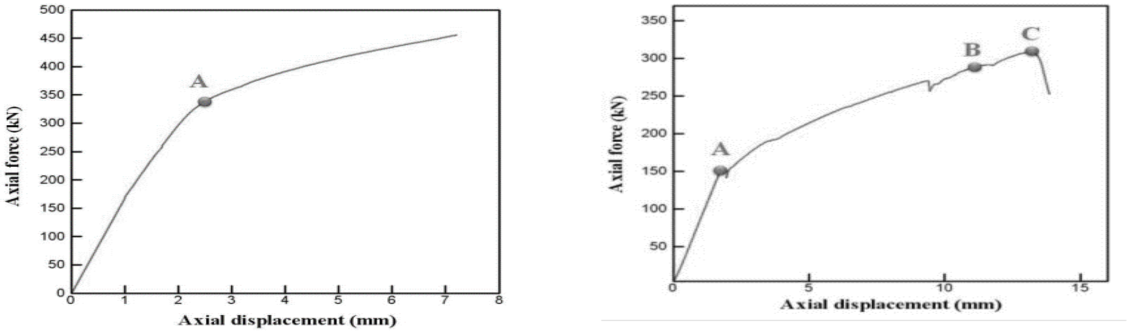
Detailings of specimen 1 and 2 are shown in figure 4. the axial force-axial displacement response was recorded by UTM. Figure 5 shows the axial force-axial displacement response of the first test specimen



(a)

(b)

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



A)   Test 1

B)   Test 2

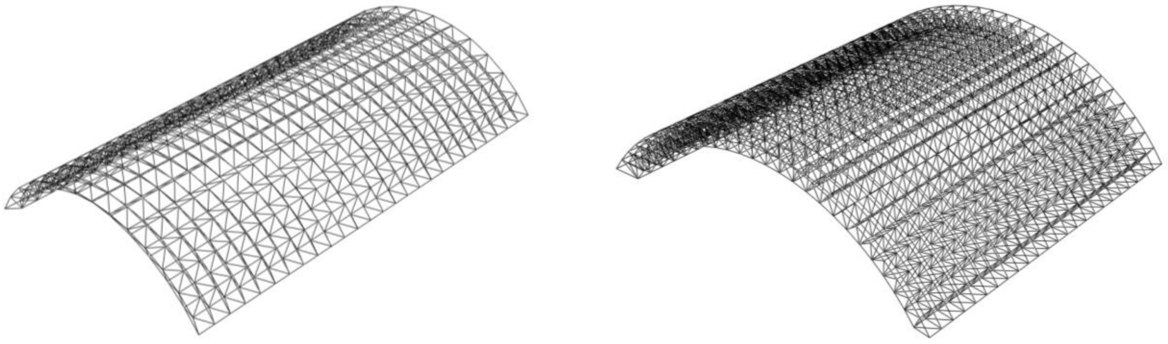
Figure 5: The axial force-axial displacement response of test 1 and test 2 [14]

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 barrel vaults

3.1. Design of double layer barrel vaults

The present parametric study involves two models of double layer barrel vaults equipped and not equipped with AFLD. All the models have square on square configuration. Models are shown in figure 6. Properties of models are mentioned in table 1. 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. Three earthquake records (each consisting vertical as well as horizontal components simultaneously) are applied to models. Details of records are shown in Table 2.



A) Model 1

B) Model 2

Figure 6: Configuration of model 1 and model 2

Table 1. Properties of models

Model number	Length (m)	Span (m)	Rise (m)	Rise to Span
1	100	40	4	0.1
2	100	40	12	0.3

Table 2. Details of earthquake records

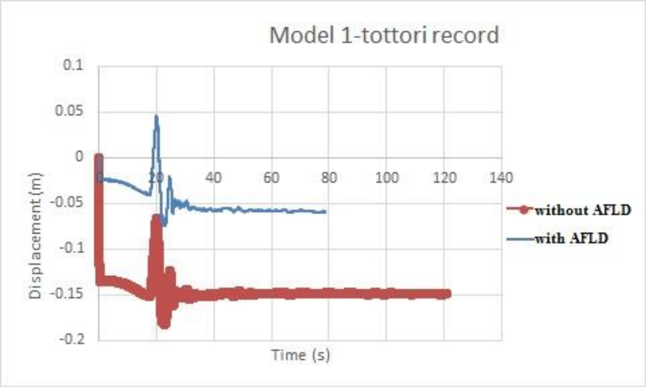
Record Name	Year	Station name	Magnitude	PGA (g)
Tottori	2000	TTR009	6.61	0.63
Bam	2003	Bam	6.6	0.8
Kobe	1995	Nishi-Akashi 1995	6.9	0.8

3.2. Time history analysis of double layer grids

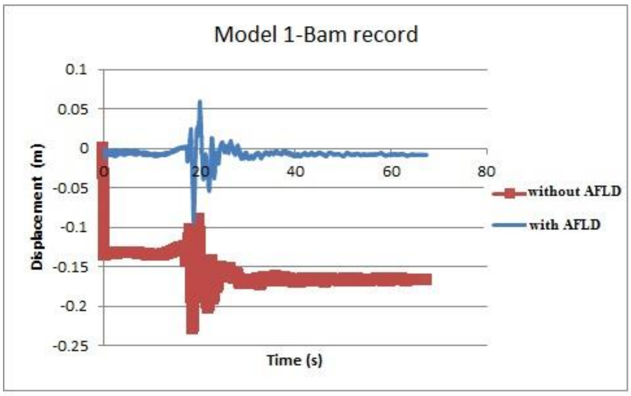
Nonlinear time history analysis are carried out in ABAQUS finite element software. Damping ratio is assumed to be 0.05. First of all models are subjected to gravity loads. Then earthquake records are applied to models. In order to investigate AFLDs effect on seismic behavior of double layer barrel vaults, critical members are identified and substituted with AFLD made from ck45 carbon steel. Critical members usually occur near supports. Finally models equipped with AFLD are subjected to aforementioned earthquake records.

4. Conclusions

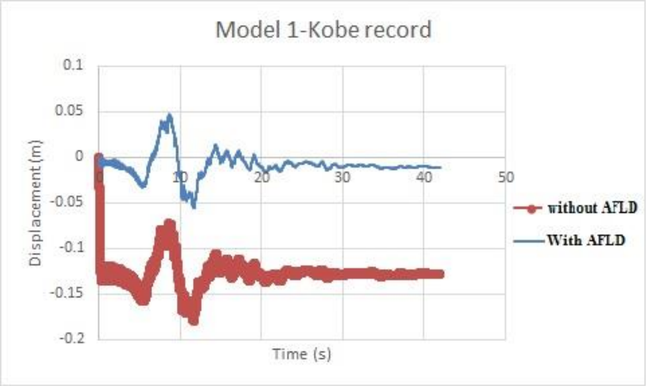
Displacement of central joint in all models which (equipped and non-equipped with AFLD) subjected to three records is mentioned in figure 7 and 8. Results indicate that by applying AFLD displacement of joints are significantly reduced.



a) Tottori record

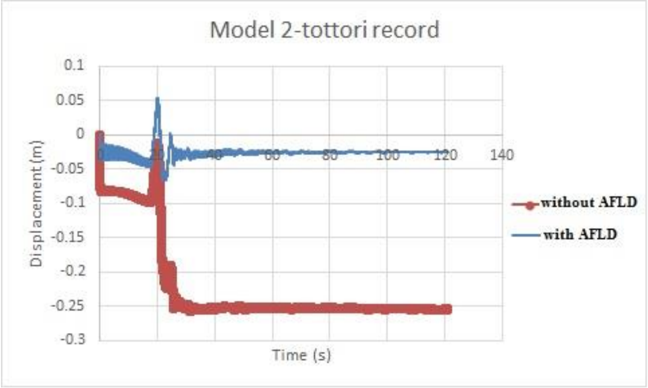


b) Bam record

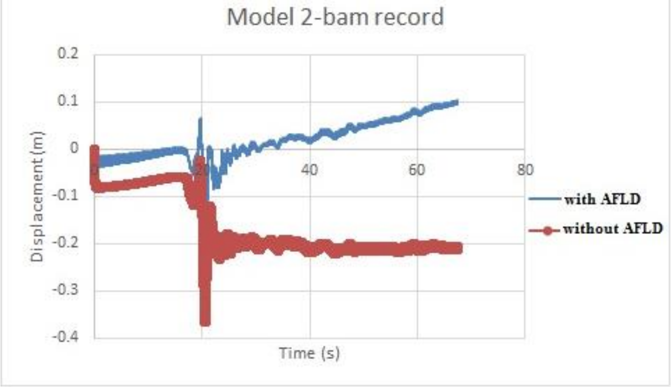


c) Kobe record

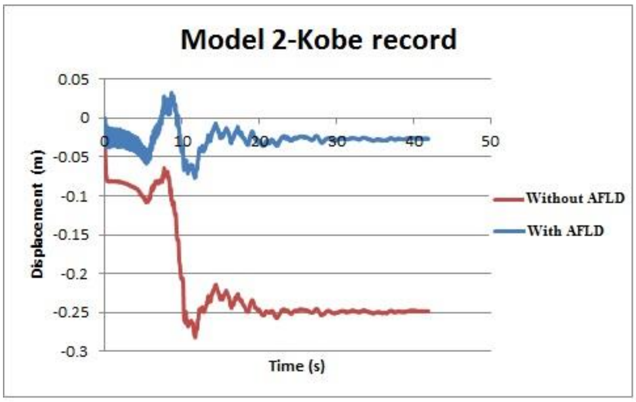
Figure 7: time history displacement of central node in model 1 subjected to earthquake records



a) Tottori record



b) Bam record



c) Kobe record

Figure 8: time history displacement of central node in model 2 subjected to earthquake records

For the double layer barrel vault in model 1 with rise to span ratio of 0.1, 63 members are substituted with AFLD. Vertical component of axial displacement for central top point was -0.180, -0.229 and -0.175 meters (for tottori, bam and kobe records respectively). Applying AFLD to 63 critical members lead to -0.07, -0.088 and -0.055 meters of central point displacement (for tottori, bam and kobe records respectively). In model 2 with rise to span ratio of 0.3, 48 critical members are substituted with AFLD. Results show that vertical displacement of -0.253, -0.365 and -0.28 altered to -0.065, -0.270 and -0.07

(for tottori, bam and kobe records respectively). Results indicate that, in all models, regardless of span ratio and record type, applying AFLD lead to decrease vertical displacement of central joint.

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