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"Research Note"

INVESTIGATION INTO THE BEHAVIOUR OF A DUCTILE MULTI-TUBULAR FORCE LIMITING DEVICE[*]

K. ABEDI[1**] AND G. A. R. PARKE[2]

[1]Associate Professor, Department of Civil Engineering, Sahand University of Technology, Tabriz, I. R. of Iran
E-mail: k_abedi@sut.ac.ir
[2]Professor, Department of Civil Engineering, University of Surrey, Guildford, Surrey GU2 5XH, UK

Abstract– A force limiting device ideally possesses rigid-plastic force/shortening characteristics. When such a device is introduced in a compression member, and if the limit load of the device is set somewhat below the buckling load of the member, the member will behave in an elastic-plastic manner. The present paper outlines the non-liner behaviour of a novel multi-tubular, ductile compression member which exhibits an initial axial stiffness, followed by a steady load plateau and subsequent enhanced stiffness and strength, before the final failure. The multi-tubular member acts as an energy absorber and force redistributor. The theoretical cyclic response of the device, obtained using ABAQUS, is presented. For a comparison of the energy absorbing characteristics, two X braced frameworks have been considered, one with conventional tubular bracing, and one with the force limiting devices used for bracing. For relatively large horizontal displacements, the framework incorporating the force limiting devices exhibited greater ductility and energy absorbing characteristics than the conventionally braced framework.

Keywords– Force limiting device, braced framework, cyclic behaviour, ductile multi-tubular member

1. INTRODUCTION

The fundamental requirements for structures located in zones of high seismic risk are primarily two-fold. To fulfill serviceability requirements, the structure must be designed to possess sufficient strength and stiffness. To fulfill the ultimate limit state requirements, the structure must be able to absorb and dissipate sufficient energy [1]. In steel structures, sufficient strength and ductility can be obtained by using a moment-resisting frame, a concentrically braced frame, or an eccentrically braced frame. An alternative system has been proposed which aims to improve the behaviour of concentrically braced frames by incorporating special members into the framework which act as force limiting devices and energy absorbers, exhibiting a large amount of ductility when loaded in compression [2]. A force limiting device ideally possesses rigid-plastic force/shortening characteristics. When such a device is introduced in a compression member, and if the limit load of the device is set somewhat below the buckling load of the member, the member will behave in an elastic-plastic manner [3]. This device would limit the compression force in the member to a pre-determined level which would remain constant under increasing deflection. Consequently, a compression member protected by a force limiting device would exhibit the elastic-plastic load-deflection characteristics instead of the highly unstable and brittle, post-buckling characteristics. The value of the load plateau set by the force limiting device must be lower than the average compression member bucking load to ensure that the device becomes operative before the member buckles. The characteristics of the force-limiting device are as follows:

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[**] Corresponding author

a) Device must be capable of providing a constant limit force with a load plateau of sufficient length;
b) The device should function with the minimum of maintenance;
c) The behavior characteristics of the device should be independent of loading sequence and time [4, 5].

There are different proposed types of force limiting devices such as: (a) rolling truss load limiter; (b) short portion of a tube, possibly constrained in a box at the end of the member; (c) the W-frame, positioned along the axis of the member between the member end and the node; (d) the extrusion damper, which operates by pushing or pulling a bulged shaft through the centre of a constricted tube lined internally with lead [6].

Parke [4, 5] has proposed special triple-tube bracing members which act as force limiting devices and energy absorbers, exhibiting a large amount of ductility. Figure 1 gives details of a force limiting device (FLD) that has been fabricated and tested in both compression and tension. This particular force limiting device consists of two steel square hollow section tubes and four steel strips. The two tubes have been carefully proportioned so that the smaller tube, plus the strip, just fit inside the large tube. Each steel strip is plug welded to the top of the outside tube and also fillet welded to the bottom of the inner tube; one strip welded onto each face of the tubes, as shown in Fig. 1. Parke has carried out experimental investigation in order to find the axial load-axial strain relationship of this force limiting device which has been tested in compression under displacement control at an initial strain rate of 0.006% per minute [4].

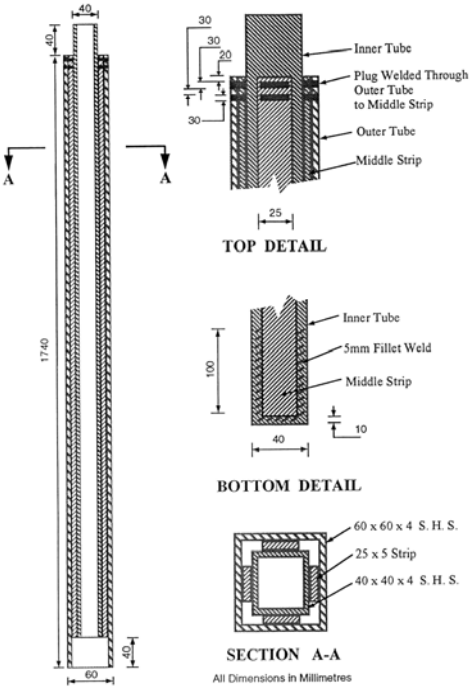

Fig. 1. Force limiting device

2. THEORETICAL BEHAVIOUR OF THE TRIPLE -TUBE FORCE LIMITING DEVICE

a) Static monotonic loading

In order to study the behaviour of the triple–tube force limiting device and to ascertain its general characteristics, geometric and material nonlinear finite element analysis should be undertaken. All of the analyses in the present study have been undertaken using ABAQUS. The finite element model of the member shown in Fig. 1 has been assembled (Fig 2). To simplify the analysis, the four middle strips in Fig. 1 have been replaced by a square tube with an equal cross-sectional area. Figure 2 shows both the full mesh and for clarity, a simplified mesh. The full mesh was used in the finite element analysis and consisted of over 950, four nodded, doubly curved, thin shell elements, with six degrees of freedom per node (Fig. 2). The static analysis was allowed for both geometric and material non-linear behaviour. In order to trace the equilibrium paths through limit points into the post-critical range, the modified Arc-Length-Riks method has been used. The material properties for each tube are given in Table 1, which has been obtained from a series of coupon tests.

Table 1. Material properties for force limiting device in Fig. 1

Tube type	Size (mm)	Wall thickness (mm)	Yield stress (N/mm^2)	Strain at yield (ε_y)	Plateau length	Elastic modulus (N/mm^2)	Hardening modulus (N/mm^2)	Ultimate strength (N/mm^2)
Outer	58 x 58	4.2	370	0.00176	15 (ε_y)	2.1 x 10^5	2.1 x 10^3	490
Middle	49.6 x 49.6	2.7	305	0.00145	15 (ε_y)	2.1 x 10^5	2.1 x 10^3	470
Inner	44.2 x 44.2	3.5	390	0.00186	15 (ε_y)	2.1 x 10^5	2.1 x 10^3	505

All three tubes in the numerical model were given an initial imperfection consisting of a maximum horizontal displacement of 1.21mm at mid-height, corresponding to the values measured on the actual force limiting device shown in Fig 1. The finite element model was supported so that it behaved as a pin-ended member and was strained under displacement controlled loading. Fig 3 shows the experimental and numerical axial load-axial end displacement responses of the force limiting device, strained in compression. According to the experimental study, the member yielded at a load of 152.9kN and buckled at a load of 331.6kN. The numerical study shows the triple-tube element yielded at a load of 154.490kN and had an ultimate capacity of 340.46kN. The figure shows that the initial stiffness, the extent of the plastic yield plateau, the ultimate capacity and the load shedding characteristics compare favourably with the actual behaviour obtained in the test programme. At failure, the load in the outer, middle and inner tubes were 139.5kN and 116.5kN respectively, indicating that the force limiting device when the middle tube reached its critical buckling load, and the outer and inner tubes were at 56% and 110% respectively, of their critical buckling loads. The behaviour of the force limiting device, shown in Fig 3, indicates that the device is capable of absorbing large amounts of energy when loaded both in compression and tension. The ultimate capacity of the device depends on the interaction occurring between the three tubes. As the member approaches its ultimate capacity, it is possible for the inner tube, which has unloaded from its tensile yield plateau, to provide the buckling restraint to both the inner and outer tubes, allowing these members to exceed their individual pin-ended bucking capacity.

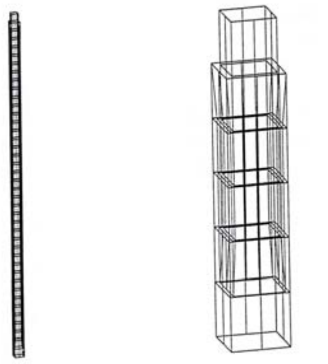

Fig. 2. Finite element mesh

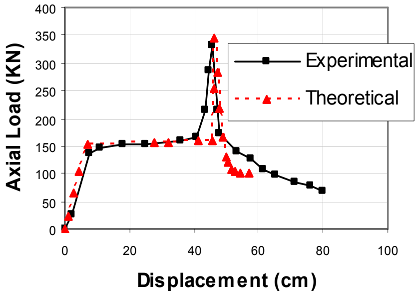

Fig. 3. Experimental and numerical responses

b) Static cyclic loading

To determine the theoretical energy absorbing characteristics of the force limiting device, the member was cycled in tension and then in compression, both over a range of approximately 43mm. Figures 4 and 5 show the cyclic axial load-axial end displacement responses obtained from the finite element analysis for the force limiting device cycled in tension and compression respectively over a range of 0-45-0mm. Table 2 gives the amount of energy absorbed due to plastic deformation, in the middle tube of the force limiting device, for each tension and compression cycle. It can be seen from these figures that, after the second cycle, there is a gradual deterioration in the energy absorbing capacity of the device as the number of cycles increases. Due to the design of the force limiting device, the cyclic behaviour of the member in both tension and compression is very similar. The energy absorbed during each cycle does show some reduction due to the Bauschinger effect.

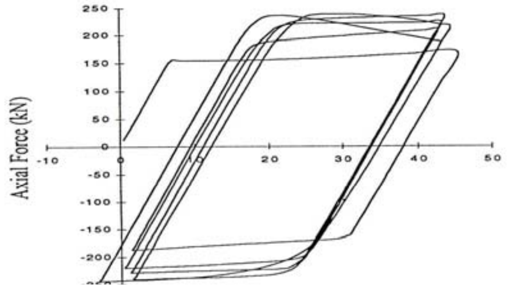

Fig. 4. Cyclic tensile behaviour of force limiting device

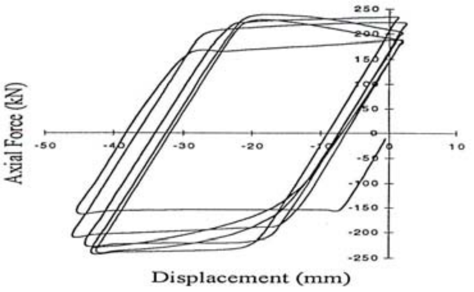

Fig. 5. Cyclic compressive behaviour of force limiting device

Table 2. Energy absorbed in the force limiting device under tension and compression cycles

Cycle number	Tension cycle 0.0 to + 45.0 to 0.0 (mm) energy absorbed (kN.m)	Compression cycle 0.0 to - 45.0 to 0.0 (mm) energy absorbed (kN.m)
1	11.13	11.47
2	10.41	12.35
3	10.40	11.63
4	10.30	10.52
5	10.20	10.49

3. THEORETICAL BEHAVIOUR OF AN ‘X’ BRACED FRAMEWORK

To determine if the incorporation of the force limiting devices into a framework will enhance the energy absorbing characteristics of the structure, the behaviour of a simple braced framework, both with and without the force limiting device, has been investigated numerically. Fig 6 shows the theoretical test framework used to compare the energy absorbing characteristics of the force limiting device. Two frames were considered, one braced using conventional steel tubing, and one braced using force limiting devices.

For all of the numerical studies, the framework was considered to have full moment beam to column connections and fixed bases; however the bracing members were considered to be pinned at both ends to the framework. In addition, both columns were supporting axial loads of 1000kN, approximately one quarter of their ultimate capacity in this framework. To assess the ductility of the braced framework, with and without the force limiting devices, the two frameworks were each cycled through two ranges of horizontal displacement namely, 50mm and 100mm, applied at the top of the framework.

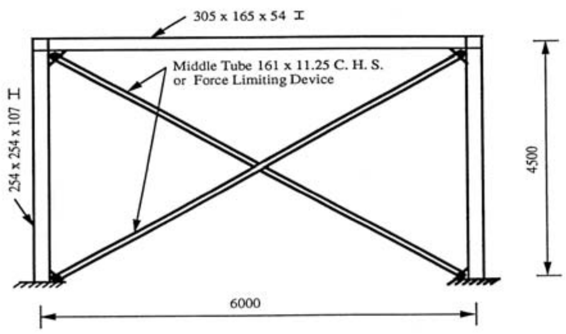

Fig. 6. Theoretical test framework

a) Framework braced with tubes

The first framework considered was braced with two tubes, both of which had an outside diameter of 166mm and a wall thickness of 11.25mm. These tubes had a slenderness ratio of 141.24, and consequently exhibited a moderately gentle, post buckling, unloading path. Each individual bracing member was modeled in the non-linear finite element analysis by using ten, two nodded Timoshenko beam elements with three active degrees of freedom at each node. An initial imperfection of 0.001L was applied to each of the two braces and their material characteristics were assumed to be elastic with a yield stress of 355N/mm^2 perfectly plastic, without strain hardening characteristics. Figures 7 and 8 show the cyclic behaviour of the braced framework subjected to a horizontal displacement at the top right hand node of ±50mm and ±100mm, respectively. The energy absorbed due to the plastic deformation is tabulated for each cycle in Table 3, indicating the rapid deterioration of the energy absorption capacity of the structural system as the number of cycles increases. The abrupt change and pinching of the hysteresis loops is primarily due to the buckling of the compression brace.

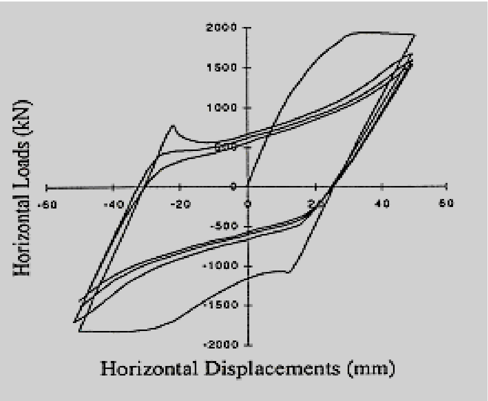

Fig. 7. Cyclic behaviour of tubular braced framework – cycle±50mm

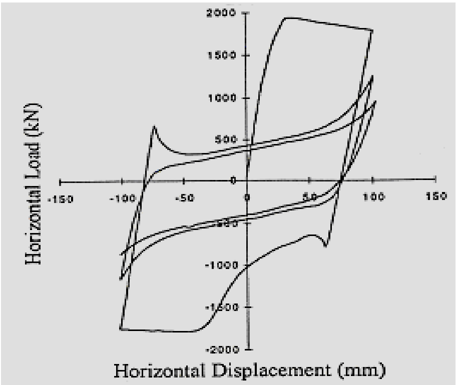

Fig. 8. Cyclic behaviour of tubular braced framework – cycle±100mm

Table 3. Energy absorbed in tubular braced framework

Cycle number	Energy absorbed (kN.m) cycle ±50mm	Energy absorbed (kN.m) cycle ±100mm
1	144.86	369.91
2	99.23	155.37

b) Framework braced with force limiting devices

The force limiting device used for the 'X' bracing in the framework shown in Fig. 6 consisted of three tubes, the properties of which are given in Table 4.

Table 4. Material properties for the theoretical force limiting device

Tube type	Diameter (mm)	Wall thickness (mm)	Yield stress (N/mm^2)	Strain at yield (ε_y)	Plateau length	Elastic modulus (N/mm^2)	Hardening modulus (N/mm^2)	Ultimate strength (N/mm^2)
Outer	193.7	16	355	0.00169	50 (ε_y)	2.1×10^5	2.1×10^3	355
Middle	161	11.25	355	0.00169	50 (ε_y)	2.1×10^5	2.1×10^3	355
Inner	138	14.5	355	0.00169	50 (ε_y)	2.1×10^5	2.1×10^3	355

The central tube of the force limiting device was the same size tube as that used in the first 'X' braced framework. The force limiting device was designed to yield at a compression load of 1880kN and exhibit a plastic load plateau of at least 200mm in both tension and compression. The FLD braces were treated as single, pin-ended elements in the finite element analysis, exhibiting perfect elastic, plastic behaviour in both tension and compression. Figures 9 and 10 show the cyclic behaviour of the framework, incorporating to FLDs, subject to a horizontal displacement at the top right-hand node of ±50mm and ±100mm, respectively. Table 5 gives the amount of energy dissipated due to the plastic deformation for each cycle, indicating that for the limited number of cycles investigated, the energy absorbing capacity of the framework incorporating the force limiting devices has increased with each cycle.

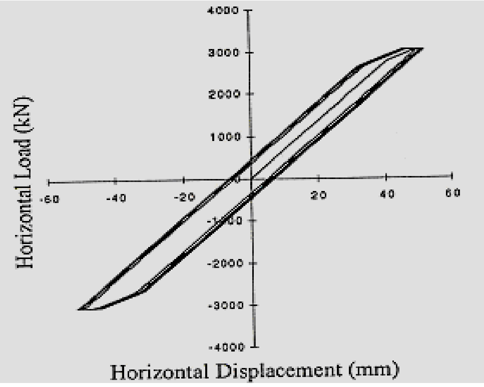

Fig. 9. Cyclic behaviour of tubular braced with force limiting device–cycle±50mm

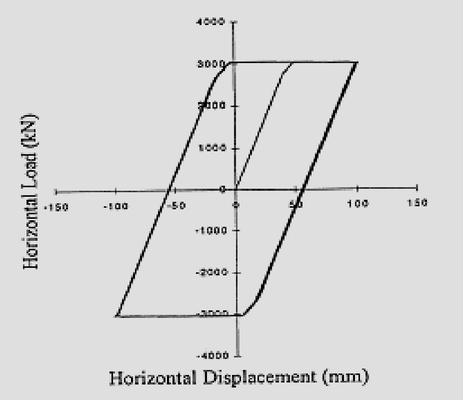

Fig.10. Cyclic behaviour of tubular braced with force limiting device–cycle±100mm

Table 5. Energy absorbed in the framework braced with force limiting devices

Cycle number	Energy absorbed (kN.m) cycle ±50mm	Energy absorbed (kN.m) cycle ±100mm
1	58.32	532.54
2	63.36	677.76

4. CONCLUSION

A compression member, protected by a force limiting device, would exhibit the elastic-plastic load deflection characteristics instead of the highly unstable, brittle, post-buckling characteristics. From both the earlier reported experimental work and the numerical investigation presented, it is evident that the proposed force limiting device is capable of exhibiting extensive ductility and absorbing large amounts of energy, due to the plastic deformation of the middle tube, under both tension and compression loading. The incorporation of the device into a framework such as X bracing, initially proved to show unfavourable characteristics, primarily due to the relatively low stiffness of the device. However, as the magnitude of the horizontal displacement acting on the framework incorporating the force limiting device increased, the extent of plastic deformation occurring in the middle tube of the device considerably increased, allowing the energy absorbing capacity of the framework to be substantially greater than the conventionally braced framework.

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