PERFORMANCE OF AN INNOVATIVE BEAM-TO-COLUMN/BRACE-TO-FRAME CONNECTION UNDER MONOTONIC AND CYCLIC SHEAR LOADING

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ABSTRACT :

A new general structural connection with the ability to connect various structural elements of any material to one another was invented. In contrary to all existing connections, it has a high shear deformation capacity which can be exploited in various circumstances including as a bracing-to-frame connection in concentrically-braced frames to reduce their high elastic stiffness. In this way, their natural frequencies decrease which in turn lead to a decline in their earthquake induced forces. This high shear deformation capacity which can be accompanied by high strength and stiffness is the source for its high energy dissipation capacity. The results of a number of monotonic as well as cyclic shear tests on various specimens of this connection with different dimensions are reported here. The monotonic tests results clearly show the high shear deformation capacity of this connection which was accompanied with high shear strength and stiffness. The hysteresis loops obtained through cyclic tests, which were 'stable' and 'well-rounded,' however, show the ability of this connection to dissipate energy in an efficient manner.

KEYWORDS: shear behaviour, steel structural joints, brace-to-frame connections, beam-to-column connections, replaceable joints, energy dissipation.

1. INTRODUCTION

The history of earthquakes which have shaken various parts of this world so far is full of tragic stories about the grief and miseries of mankind caused by Nature. From the very old earthquakes of New Madrid, USA, in 1811-1812, with up to 8.1 magnitude, to more recent ones of 6.6 magnitude of City of Bam, Iran, 2003, and that of 7.9 magnitude of Sichuan Province, China, 2008, which had a death toll of more than 80'000 and made more than 5 million people homeless, all involve lessons to be learned by everyone, specifically structural engineers. In fact these lessons, to a great extent, have already been learned and much progress has been made in our knowledge on the nature of earthquakes, and in the measures which can be taken to reduce their destruction. Though, by no means we can claim that we can design and build buildings and other installations which will be safe during 'any' earthquake. The variety of the involving factors with which an earthquake is described, and the uncertainties which surround any of these factors, deprive us from making any statement with a high degree of confidence about earthquakes and the degree of safety of our structures during such events, no matter how carefully and skillfully they are designed and constructed.

The measures taken by structural engineers to safeguard a building against the prospective damage of earthquakes are quite wide and diverse. While 'active controlling' of structures is still not a common practice, 'passive control' of their behaviour is more widely used. Active or passive, whichever method is adopted, the structure requires possessing a good degree of ductility to reduce its natural frequencies, hence its earthquake induced forces. On the other hand, overall ductility has a direct relation with the formation of plastic hinges in the structure during an overload. Despite the fact that this process and its associated dissipated energy, in particular in a cyclic loading context, is crucial in the performance of the structure during an earthquake, however, the remaining post-event 'survived' structure, may not be of much further use. The cost of repairing such structure, which may well require the replacement of damaged beams and columns, could be enormous. On the other hand, the replacement of connections seems to be a more viable and cost-effective solution. This requires a totally different approach and a total revision in all the concepts and criteria devised and used for the design of structures for earthquake prone areas. Now the very important role of energy dissipation should be given to the connections. This means that the connections should have a high energy dissipation capacity together with being replaceable. A noteworthy point in this regard is that if a connection does not work in a 'sacrificial' capacity, mere use of bolts to fasten it to the beam and column cannot necessarily guarantee its 'replaceability.' The invented connection, described in this paper, is designed to fulfill all these requirements.

The ability of this connection to undergo large shear displacements under shear loading makes it a good candidate for being used as a beam-to-column connection to decelerate the progressive collapse of various floors of multi-storey buildings onto one another. Moreover, this ability together with its performance under cyclic loading promotes its application as a bracing-to-frame connection. In particular, with regard to concentrically-braced frames (CBFs), it can highly increase the ductility of such frames, which would otherwise badly suffer from its absence.

The work presented in this paper comprises the recent study of the behaviour of 'mild steel' specimens of this connection under 'monotonic' and 'cyclic' 'shear loadings.' This connection, as already shown through experiments, also through new tests which are reported in this paper, has an exclusive large shear deformation capacity. This shear deformation capacity can be accompanied by large shear stiffness and large shear strength, and it is adjustable to the desire of the designer which is normally based on the demand of the structure in which it is to be fitted.

2. THE INVENTED CONNECTION (KHONSAR™)

Despite the extensive description of the devised connection in previous papers (see Khonsari *et al.* (2001) & Khonsari *et al.* (2004)), a brief introduction is given here. The developed connection, named KHONSAR™, is composed of two attachment plates which attach it to the face of the flange of the column and the end-plate of the beam, which is intended to be connected to the column. These attachment plates embrace a number of cylindrical tubes, which deform when bending moment is transferred between the beam and the column connected by this connection. The tube(s) are laid either in a parallel or in a perpendicular relation with the axis of bending. By using tubes made of ductile materials, they can absorb and dissipate much energy upon overloading of the joint. Figs. 1 & 2 depict the two versions of this connection, the one with tubes parallel with the axis of bending (HLT, Horizontally-Laid-Tubes version), and the one with the tube(s) perpendicular to the axis of bending (VLT, Vertically-Laid-Tubes version). The embrittlement effects of the connection, caused by welding the tubes to the attachment plates, can be eliminated to a great extent by annealing the connection unit, which is a separate unit of limited volume—conventional welded connections become as a single unit with the beam and the column they connect and the combination becomes too large to be housed in an annealing oven. However, while the HLT version has a great capacity of deformation both in bending and shear, the VLT version has just a high rotational capacity, and is basically 'locked' in shear, as all the other existing connections are.

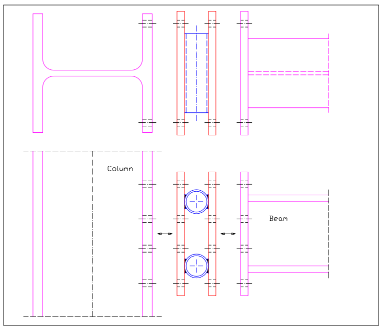

Figure 1- The Horizontally-Laid-Tubes (HLT) version of KHONSAR™, with high 'rotational' as well as 'shear' deformation capacity.

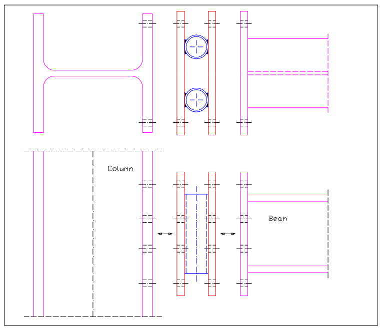

Figure 2- The Vertically-Laid-Tubes (VLT) version of KHONSAR™ with just high 'rotational' deformation capacity.

3. EXPERIMENTAL STUDIES

In addition to previous work on 'steel' and 'aluminium' specimens, already reported in previous papers, Khonsari *et al.* (2005) and Khonsari *et al.* (2006), new tests were carried out on 'Mild Steel' specimens, which are reported here. These tests can also be categorized into two following types.

1. Tests carried out under monotonic loading regime, which in turn, subjected the specimens to monotonic shear loading.
2. Tests carried out under cyclic loading regime, which in turn, subjected the specimens to cyclic shear loading.

These tests were all carried out using the test setup shown in Fig. 3, the same modified setup used for some of the previous tests. The differences between this modified version and the initial version of the test setup were discussed in Khonsari *et al.* (2006).

The specimens used in these series of tests were all made from 'Mild Steel' tubes with two different sizes, explained in Table 1. One of the reasons for testing such limited number of specimens was the obligation of the authors to use mild steel, as a highly ductile material, and the limited number of sizes of 'structural' circular tubes, made of this material, available in the market.

Table 1- Geometrical and Material properties of the tubes used in the specimens of each test assembly.

Test Series* (Specimen)	D† (mm)	t‡ (mm)	D_m/t§	L¶ (mm)	Material**
HLT-St-Sh-1-M	72	6	11	100	St37
HLT-St-Sh-1-C	72	6	11	100	St37
HLT-St-Sh-2-M	60	5	11	100	St37
HLT-St-Sh-2-C	60	5	11	100	St37

*- notations: HLT, Horizontally-Laid-Tubes Version of the connection; St, Steel; Sh, under Shear loading; 1 & 2, the specimen number; M, Monotonic loading regime; C, Cyclic loading regime,
†- nominal outside diameter of the tubes,
‡- nominal thickness of the tubes,
§- the ratio of mean diameter to thickness of the tubes,
¶- nominal length of the tubes,
**- material type based on DIN standards, approximately equivalent to A36 of ASTM.

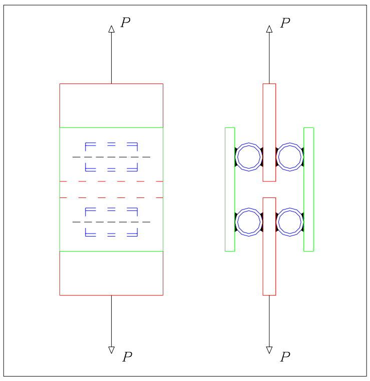

Figure 3- The modified test assembly, applicable to both 'monotonic' and 'cyclic' tests.

3.1. Monotonic Tests

This part of the work comprises tests carried out on two assemblies, HLT-St-Sh-1-M & HLT-St-Sh-2-M, each employing tubes of a certain size (see Table 1). These assemblies were subjected to 'monotonic tensile loading,' with a rate of displacement of

$$\frac{\mathrm{d}\Delta}{\mathrm{d}t} = 0.1 \quad \text{mm/sec}$$

where Δ is the extension applied to the assembly by the universal testing machine, and t denotes the time. The reason for using a low speed of loading was to reduce the strain rate effects on the material of the specimens, mild steel, which is known to be highly rate sensitive.

Figs. 4, 5 & 6 depict the 1st and Figs. 7, 8 & 9 depict the 2nd test assemblies, 'before,' at the 'middle of,' and 'after' the tests. The 'average' shear force-shear displacement curves for either tube of the two test assemblies are shown in Figs. 10 & 11.

The tubes of both assemblies behaved very well under monotonic loading, without showing any sign of failure. Both tests were terminated when the load on the assemblies started to rise sharply, mostly due to the tubes entering a 'tension' phase, after passing the initial 'shear' phase of their behaviour. This can be identified on the curves of Figs. 10 & 11, where the slope at the middle of the plastic deformation of the tubes changes.

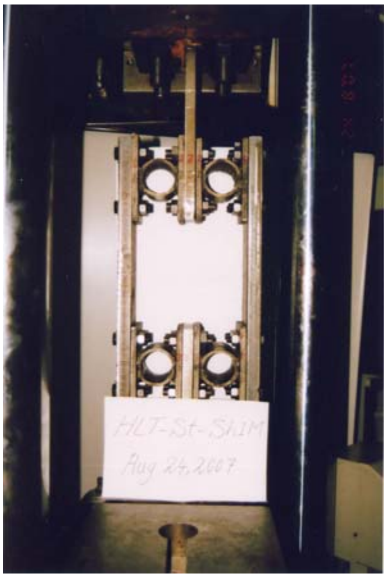

Figure 4- First series of monotonically tested specimens, HLT-St-Sh-1-M, before the test.

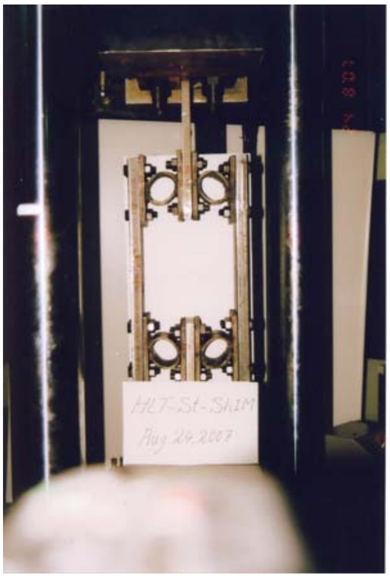

Figure 5- First series of monotonically tested specimens, HLT-St-Sh-1-M, at the middle of the test.

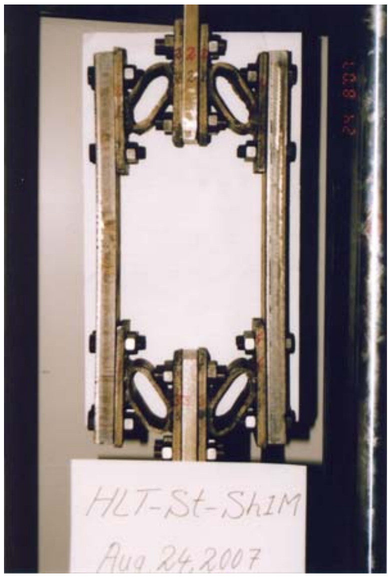

Figure 6- First series of monotonically tested specimens, HLT-St-Sh-1-M, after the test.

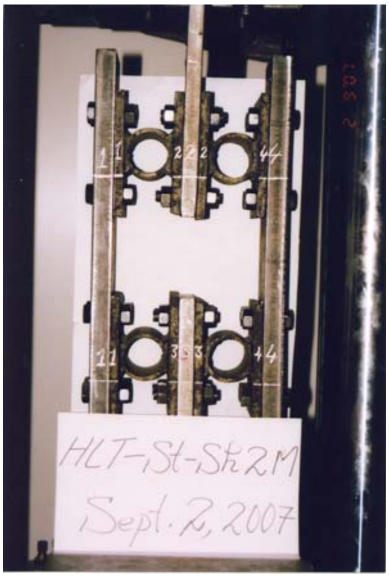

Figure 7- Second series of monotonically tested specimens, HLT-St-Sh-2-M, before the test.

Figure 8- Second series of monotonically tested specimens, HLT-St-Sh-2-M, at the middle of the test.

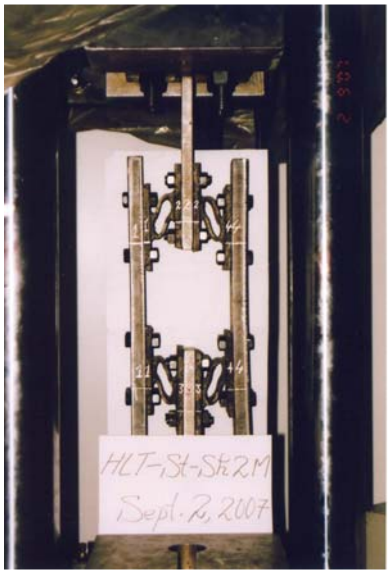

Figure 9- Second series of monotonically tested specimens, HLT-St-Sh-2-M, after the test.

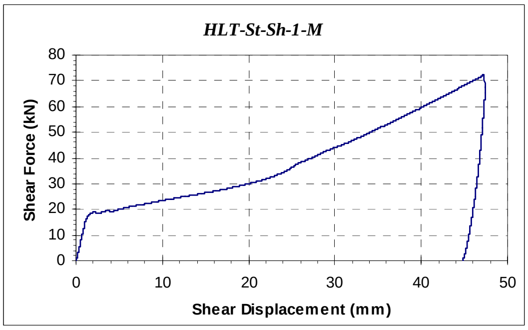

Fig. 10- ‘Average’ Shear Force-Shear Displacement curve of one of the tubes of the 1st test assembly, HLT-St-Sh-1-M, tested under monotonic loading.

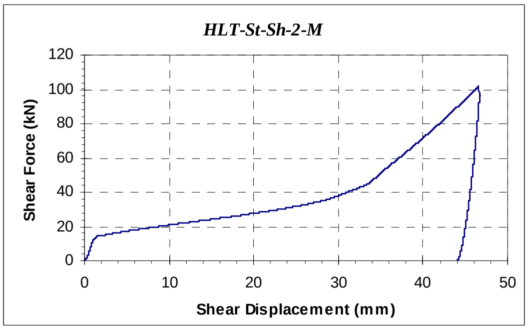

Fig. 11- ‘Average’ Shear Force-Shear Displacement curve of one of the tubes of the 2nd test assembly, HLT-St-Sh-2-M, tested under monotonic loading.

3.2. Cyclic Tests

Specimens nominally identical to those tested under monotonic loading were fabricated and tested under cyclic loading. While for testing connections under cyclic ‘bending,’ guidelines are given by ATC (1992), AISC (1997) and AISC (2002), since so far no other structural connection with the ability to deform under shear loading existed, the need for devising such guidelines has not arisen. Therefore, the authors, using the guidelines for bending, devised their own pattern of cyclic loading for ‘shear.’ This pattern is shown in the first three columns of Table 2 and is graphically demonstrated in Fig. 12.

Table 2- Values of the amplitudes of displacements and the number of cycles of sinusoidal loading used for each loading stage, together with the period of each cycle and the total time of each stage of loading.

Stage	No. of Cycles	Amplitude (mm)	Period (sec)	Total Time (sec)
1	6	$0.5\Delta y$=1.25	25	150
2	3	Δy=2.50	50	150
3	3	$1.5\Delta y$=3.75	75	225
4	3	$2\Delta y$=5	100	300
5	3	$4\Delta y$=10	200	600
6	3	$6\Delta y$=15	300	900
7	3	$8\Delta y$=20	400	1200
8	3	$10\Delta y$=25	500	1500

In the above, Δy is the shear deflection of each tube identified on the Shear Force-Shear Displacement curve of each monotonically-tested tube where first yield was estimated to have occurred (see Figs. 10 & 11). Incidentally, the two values of Δy for the tubes of the two test assemblies were approximately the same, i.e. 2.5 mm. Fig. 12 depicts the variation of the amplitude of shear deformation of each tube with time.

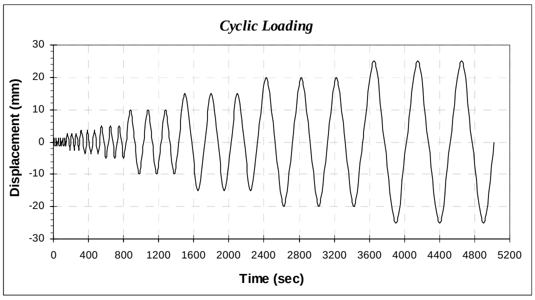

Figure 12- The variation of amplitude of shear deformation of each tube with time, given to the Universal Testing Machine (the amplitude of the crosshead was double this amount).

Figs. 13, 14 & 15 depict the first specimen tested under cyclic shear loading, HLT-St-Sh-1-C, before the test, at the most tensile state, and at the most compressive state, before signs of failure emerged. However, similar situations for the second specimen tested under cyclic shear loading are shown in Figs. 16, 17 & 18. Moreover, the hysteresis loops of an ‘average’ tube of the HLT-St-Sh-1-C test assembly are shown in Fig. 19 and those of an average tube of HLT-St-Sh-2-C are shown in Fig. 20.

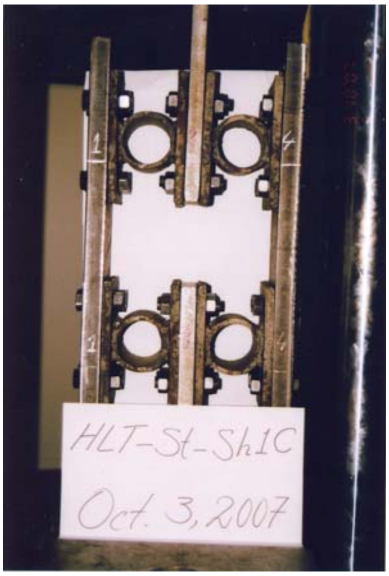

Figure 13- First series of specimens tested under cyclic loading, HLT-St-Sh-1-C, before loading.

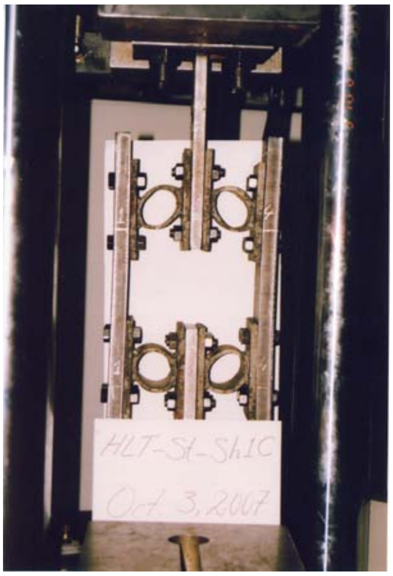

Figure 14- First series of specimens tested under cyclic loading, HLT-St-Sh-1-C, at the most overall tensile state.

Figure 15- First series of specimens tested under cyclic loading, HLT-St-Sh-1-C, at the most overall compressive state.

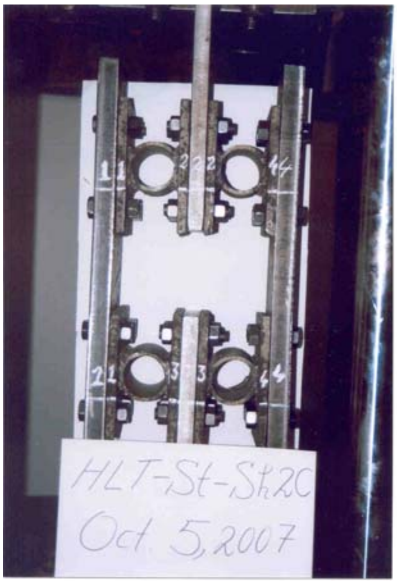

Figure 16- Second series of specimens tested under cyclic loading, HLT-St-Sh-2-C, before loading.

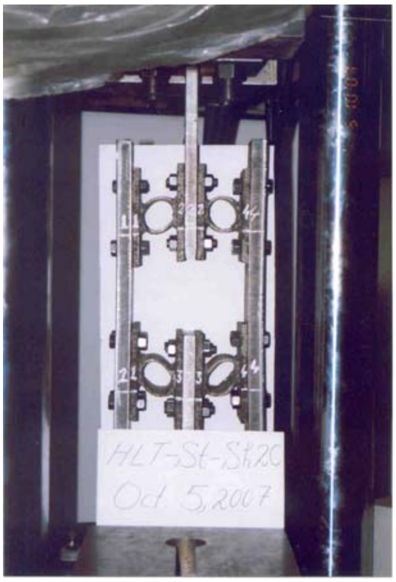

Figure 17- Second series of specimens tested under cyclic loading, HLT-St-Sh-2-C, at the most overall tensile state.

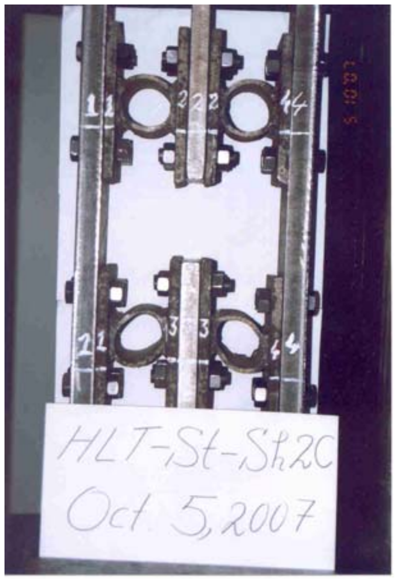

Figure 18- Second series of specimens tested under cyclic loading, HLT-St-Sh-2-C, at the most overall compressive state.

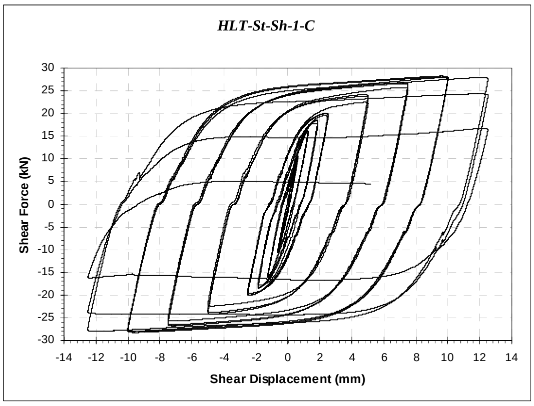

Figure 19- Hysteresis loops of an 'average' tube of the 1st cyclically loaded test assembly, HLT-St-Sh-1-C.

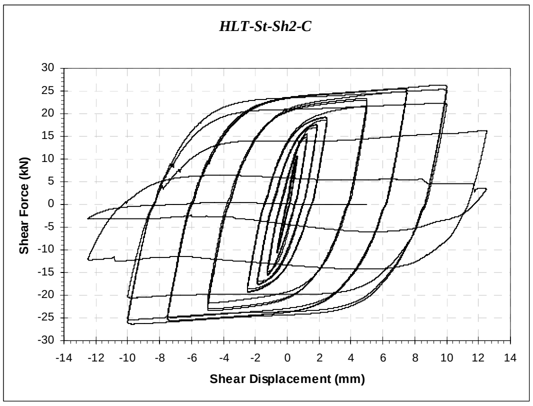

Figure 20- Hysteresis loops of an 'average' tube of the 2nd cyclically loaded test assembly, HLT-St-Sh-2-C.

In order to have a better picture of the performance of the two connections which were tested under cyclic loading, the final parts of these curves, which belong to the post-failure of the specimens and show the 'strength degradation' phase of the tubes are removed and the remaining (prior to failure) parts are shown in Figs. 21 & 22.

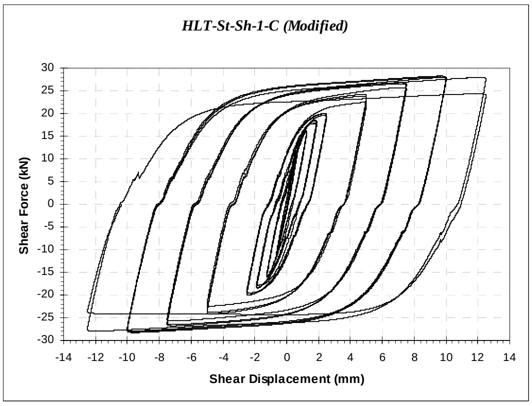

Figure 21- Hysteresis loops of an 'average' tube of the 1st cyclically loaded test assembly, HLT-St-Sh-1-C, before serious strength degradation starts.

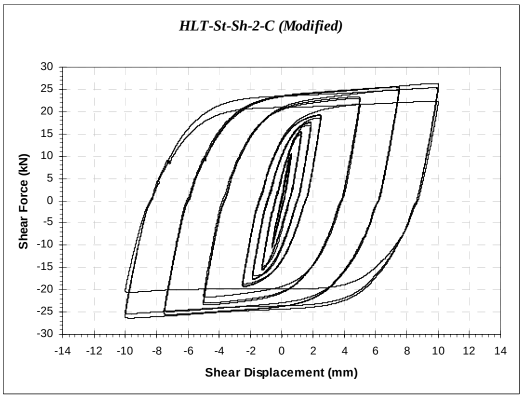

Figure 22- Hysteresis loops of an 'average' tube of the 2nd cyclically loaded test assembly, HLT-St-Sh-2-C, before serious strength degradation starts.

While Figs. 19, 20, 21 & 22 clearly give qualitative and, to some extent, quantitative indications of the effectiveness of the devised connection in dissipating energy, to have a more rigorous measure of its performance in this regard, the energy dissipated by each tube within each cycle of loading, that within each stage of loading, the average amount of dissipated energy per cycle, and the density of this average value are calculated and presented in Tables 3 & 4.

Table 3- The energy dissipation characteristics of a typical tube of the 1st test assembly, HLT-St-Sh-1-C, subjected to cyclic loading.

Stage	Cycle	Dissipated Energy per Cycle (J)	Dissipated Energy per Stage (J)	Average Dissipated Energy per Cycle (J)	Density of Average Dissipated Energy per Cycle (kJ/m^3)
1	1	2.88	10.75	1.79	14.40
	2	1.93			
	3	1.58			
	4	1.49			
	5	1.45			
	6	1.41			
2	1	17.60	48.35	16.12	129.55
	2	16.33			
	3	14.42			
3	1	40.80	123.32	41.11	330.41
	2	42.59			
	3	39.93			
4	1	71.63	227.33	75.78	609.09
	2	78.91			
	3	76.78			
5	1	229.26	792.14	264.05	2122.40
	2	282.48			
	3	280.40			
6	1	464.25	1527.81	509.27	4093.47
	2	532.06			
	3	531.50			
7	1	734.65	2335.69	778.56	6258.04
	2	805.31			
	3	795.74			
8	1	979.43	2570.64	962.58	7737.18
	2	945.73			
	3	645.47			
Total Dissipated Energy			7636.03	n/a	n/a

Table 4- The energy dissipation characteristics of a typical tube of the 2nd test assembly, HLT-St-Sh-2-C, subjected to cyclic loading.

Stage	Cycle	Dissipated Energy per Cycle (J)	Dissipated Energy per Stage (J)	Average Dissipated Energy per Cycle (J)	Density of Average Dissipated Energy per Cycle (kJ/m^3)
1	1	3.22	13.69	2.28	26.41
	2	2.42			
	3	2.08			
	4	2.02			
	5	2.00			
	6	1.95			
2	1	19.99	60.66	20.22	234.05
	2	21.15			
	3	19.51			
3	1	46.96	151.26	50.42	583.62
	2	52.87			
	3	51.43			
4	1	82.82	265.42	88.47	1024.10
	2	91.77			
	3	90.83			
5	1	240.69	835.96	278.65	3225.52
	2	297.33			
	3	297.93			
6	1	478.83	1566.43	522.14	6044.02
	2	545.30			
	3	542.30			
7	1	728.50	2153.71	745.59	8630.49
	2	762.68			
	3	662.53			
8	1	550.34	763.94	n/a	n/a
	2	209.40			
	3	4.20			
Total Dissipated Energy			5811.07	n/a	n/a

4. DISCUSSION

Despite the fact that limited number of specimens were fabricated and tested for this experimental programme, they all performed very well and it can be claimed that it was a successful programme. Not only the tests under monotonic loading regime were carried out successfully, those under cyclic loading regime, which were more elaborate, were also carried out quite satisfactorily. Apparently, one of the factors behind this success was the quality of the welds, something which was not attained during the previous similar programme conducted on aluminium alloy specimens (see Khonsari *et al.* (2006)).

The other factor is the ductility of the material of the tubes, which according to their manufacturer was 'mild steel.' Though, the authors did not find the chance to experimentally establish this, e.g. by carrying out Quantometer and simple tension tests on the material of the tubes. However, the very ductile behaviour of the specimens, at least, does not contradict this issue.

Finally, the major contributing factor towards the ductile behaviour of the specimens is the novel geometry of the connection which, unlike all the existing connections, is not 'locked' in shear.

Regarding cyclic tests, the shape of the hysteresis loops is very good, 'stable' and 'well-rounded,' implying large amount of energy dissipation in each cycle, as also demonstrated in Tables 3 & 4.

5. APPLICATION

As explained in the above, one of the circumstances where the shear deformation capacity of this connection can be exploited is when the braces of a bracing system are to be connected to the members of the frame. Figs. 23 & 24 demonstrate such application in the first building in the world, built in Iran, where braces of s chevron bracing system are connected to the frame through KHONSAR™ connection.

Figure 23- Application of KHONSAR™ as a brace-to-frame connection.

Figure 24- A close-up of the joint of Fig. 23.

6. CONCLUSIONS

Using the tests reported in this paper as well as those reported previously, the following conclusions can be drawn.

1. The high shear deformation capacity of the HLT version of this connection is something exclusive, whereas other existing connections basically posses nil shear deformation capacity.
2. Depending on the dimensions and the proportions of the geometrical factors of the HLT version of the devised connection, its high shear deformation capacity can be accompanied by high strength as well as high stiffness, unlike other existing connections.
3. If the welding of the tubes to the attachment plates is properly exercised, and if the embrittlement effects of welding on steel components of the connection are eliminated by subjecting the connection to a proper heat treatment process, the performance of the connection under both monotonic and cyclic shear loading is much satisfactory.

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