PERFORMANCE OF AN INNOVATIVE BEAM-TO-COLUMN CONNECTION UNDER CYCLIC FLEXURAL LOADING

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ABSTRACT :

In order to respond to the great demand arising in structural connections during earthquakes, a new beam-to-column connection with high rotational capacity was devised. Due to its ability to contain damage during an overload, it leaves the connected elements intact. This, together with its replaceability can reduce the cost of post-event repair substantially. Its bending as well as shear performance under “monotonic” loading had already been assessed experimentally and proved well superior to that of conventional joints. In order to study its performance under “cyclic” flexural loading experimentally, new bending tests were conducted on mild steel specimens of the connection. These tests clearly showed the ability of the devised joint to withstand adequate number of cycles in bending and dissipate energy through well-shaped hysteresis loops. This would result in large amount of energy being dissipated in each cycle. Such very ductile response of this connection in bending is expected to be exploited in various structures located in earthquake prone areas to give rise to a ductile overall behavior of the structure.

KEYWORDS: beam-to-column connections, steel structural joints, replaceable joints, cyclic loading, energy dissipation, retrofitting, repair.

Natural disasters, in general, and earthquakes, in particular, have always threatened human lives and the existence of buildings and various installations. While there may be places on this planet which might not have experienced any serious earthquakes, many indeed have. However, we are fortunate in that many areas badly hit by earthquakes were of low population density which led to a low death toll. The 7.8 magnitude earthquake of Murchison, New Zealand, which happened in 1929, despite its severe destruction left just 17 deaths behind. Though, the recent earthquake of Sichuan Province, China, left more than 80’000 deaths and more than 5 million homeless. Taking this fact into account that most of the current towns and cities were initially established near ‘water’ resources and such resources mainly existed where ‘faults’ were formed, we can easily understand why facing earthquakes with high death and injured tolls is most of the times inevitable. The complexity of the situation stems from the ‘dilemma’ that earthquakes hit stronger structures more badly than weaker ones, though weak structures cannot sustain earthquakes anyway! Therefore, it is a very delicate task to design a structure which is strong enough to sustain service loads together with earthquakes, but not stimulate the induction of large forces in the structure which they cannot resist. While during the past half a century, since the early 60s, we have witnessed an upward trend in the R&D in this field, which was greatly accelerated after the two major earthquakes that shook the two sides of Pacific in 1994 (Northridge) and 1995 (Kobe), we are still very far from a ‘Guaranteed’ design methodology. Nevertheless, the achievements of this half a century has been great and diverse methods for improving the ‘quake-worthiness’ of structures have been developed. Base Isolation, using TLDs, Active Control, etc., etc., are all useful means of better coping with destructing consequences of earthquakes in structures. However, the easiest way for improving a structure against earthquakes is to find the weakest element of structure during such events and find a solution for it. ‘Connections’ are normally the focal points of receiving damage during any overload including that of earthquakes. The main reason for the failure of connections during earthquakes is their inability to deliver large rotations. A limiting value of 0.03 radians as the rotational capacity of connections of the most ductile steel frames, ‘special moment frames,’ given by AISC (1997), is a measure against which connections can be evaluated. However, the dilemma which exists here is that for basically all the existing connections as the rotational capacity increases, the strength and the stiffness decrease, and vice versa. Whereas, at least for structures built in earthquake prone regions, we need connections to be able to deliver larger rotations together with large strength and stiffness. The connection introduced in this paper and some previous papers, called KHONSAR, seems to be the only connection with this ability.

2. THE DEVISED CONNECTION (KHONSAR™)

Despite the extensive description of the devised connection in previous papers (Khonsari *et al.* (2001), Khonsari *et al.* (2002) & Khonsari *et al.* (2003)), a concise 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 and 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 entity 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 other existing connections are.

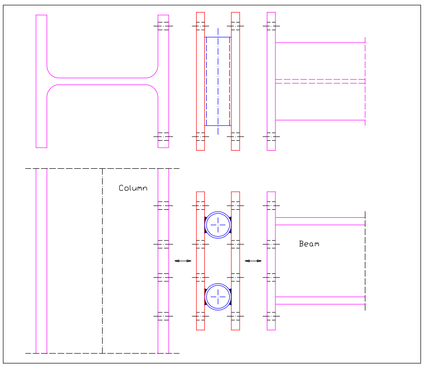

Figure 1- The Horizontally-Laid-Tubes (HLT) version of KHONSAR™, with high 'rotational' as well as 'shear' deformation capacity.

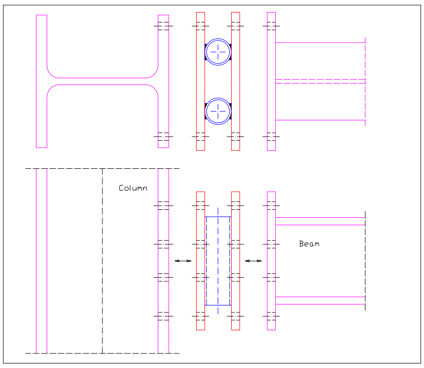

Figure 2- The Vertically-Laid-Tubes (VLT) version of KHONSAR™ with just high 'rotational' deformation capacity.

3. EXPERIMENTAL STUDIES

In addition to what was done in the past, the experimental work conducted recently on the 'bending behaviour' of this connection comprised a number of tests under 'cyclic loading' regime. This would allow the authors to have a better picture of such behaviour which, as expected, and indeed was observed, was to some extent different from that under 'monotonic loading' regime. To achieve such goal, a series of measures had to be taken, as explained below. In order to use a 'Universal Testing Machine,' which was available to the authors, instead of a combination of 'Actuator' and 'Loading Frame,' which was not available, a certain test assembly had to be designed and fabricated (see Fig. 3). Using this test assembly, altogether 3 tests, as described below, were carried out.

1. Test carried out on the assembly with specimens called HLT-C1. The two nominally-identical specimens used in this assembly were made with Mild Steel tubes with the dimensions shown in Fig. 4 and Table 1.

2. Test carried out on the assembly with specimens called HLT-C2. The specimens used in this assembly were also made with Mild Steel tubes (see Fig. 5 and Table 1), but with the distinction that in addition to the two horizontal tubes which would resist bending, a longitudinal tube was also used to force the specimens not to deform in shear mode.
3. Test carried out on the assembly with specimens called HLT-C3. The specimens used in this assembly were nominally-identical with those of HLT-C2 (see Fig. 5 and Table 1).

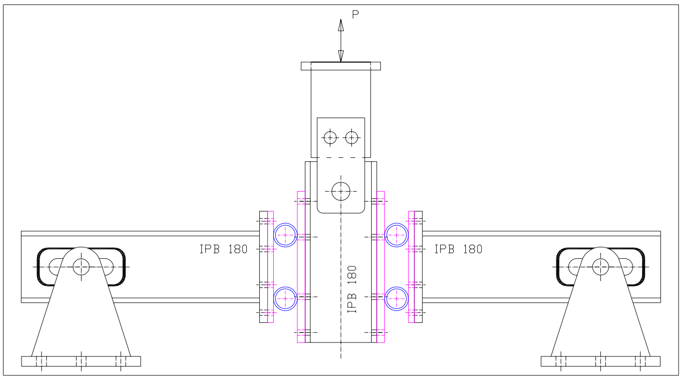

Figure 3- The test assembly designed and fabricated to enable the authors to apply cyclic loading to the specimens of the connection through UTM. IPB180 is a mid-weight wide flange section with 180 mm height and 180 mm width, based on DIN standard.

Table 1- Geometrical and Material properties of the tubes used in the specimens of each test assembly. Test Series* (Specimens).

Test Series* (Specimens)	$D^{\dagger}$ (mm)	$t^{\ddagger}$ (mm)	$\frac{D_m}{t}$ §	$L^{¶}$ (mm)	Material**
HLT-C1	48.3	3.25	13.86	100 100	St37
HLT-C2	60	5	11	100 50 100	St37
HLT-C3	60	5	11	100 50 100	St37

*- notations: HLT, Horizontally-Laid-Tubes Version of the connection; C, Cyclic loading regime; 1, 2 & 3, the specimen number.
†- nominal outside diameter of the tubes,
‡- nominal thickness of the tubes,
§- mean diameter to thickness ratio of the tubes,
¶- nominal length of the tubes used in each connection unit, the top horizontal tube, the middle (vertical) tube (if existed), and the bottom horizontal tube, respectively,
**- material type based on DIN standards, approximately equivalent to A36 of ASTM.

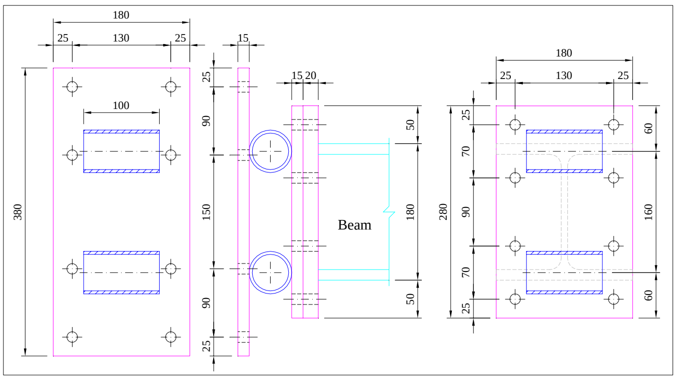

Figure 4- Details of the specimens HLT-C1 of KHONSAR™ connection.

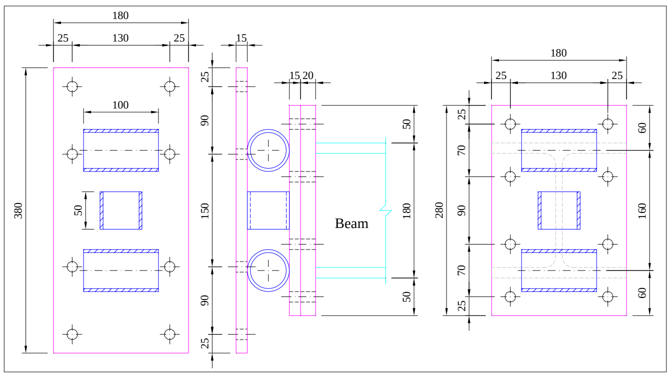

Figure 5- Details of the specimens HLT-C2 & HLT-C3 of KHONSAR™ connection.

To subject the test assemblies to cyclic loading, the guidelines given by ATC (1992), AISC (1997) & AISC (2002) were used as a basis and a loading pattern was devised by the authors which was somewhat different from those given in these publications but involved the spirit of their guidelines. Such loading pattern for the first cyclically loaded specimens, HLT-C1, is given in Table 2 and depicted in Figure 6. However, based on the experience obtained during this test, it was decided to modify the pattern of loading and that given in Table 3, depicted in Figure 7, was used for assemblies with specimens HLT-C2 and HLT-C3 (the two nominally-identical specimens). In these two Tables, y is 4 the amount of the displacement of the crosshead of the UTM at which the connection was considered to start plastic behaviour. Moreover, the amount of period (frequency) of each stage of loading for each specimen was so chosen that the rate of displacement of the crosshead would remain at the low value of

$$\frac{d\Delta}{dt} = 0.1 \qquad (mm/\sec.)$$

where Δ is the displacement 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.

Table 2- Values of the amplitudes of displacements and the number of cycles of sinusoidal loading used for each loading stage applied to the test assembly with HLT-C1 specimens, 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	$0.5\Delta_y$=1.5	58.824	353
2	3	Δ_y=3.0	125	375
3	3	$1.5\Delta_y$=4.5	166.667	500
4	3	$2.0\Delta_y$=6.	250	750
5	3	$3.0\Delta_y$=9.	333.333	1000
6	3	$4.0\Delta_y$=12.	500	1500
7	3	$5.0\Delta_y$=15.	500	1500
8	3	$6.0\Delta_y$=18.	1000	3000

Table 3- Values of the amplitudes of displacements and the number of cycles of sinusoidal loading used for each loading stage applied to the test assembly with HLT-C2 and HLTC3 specimens, 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	25.0	150
2	3	Δ_y=2.5	50.0	150
3	3	$1.5\Delta_y$=3.75	76.923	231
4	3	$2.0\Delta_y$=5.0	100	300
5	3	$3.0\Delta_y$=10.0	200	600
6	3	$4.0\Delta_y$=15.0	333.333	1000
7	3	$5.0\Delta_y$=20.0	333.333	1000
8	3	$6.0\Delta_y$=25.0	500	1500

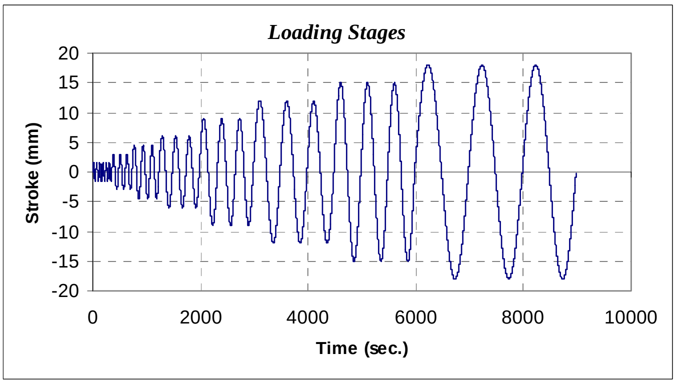

Figure 6- The variation of amplitude of the stroke, given to the Universal Testing Machine for test assembly with HLTC1 specimens.

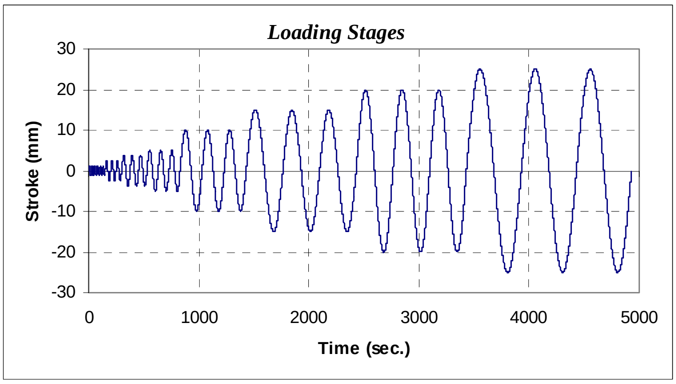

Figure 7- The variation of amplitude of the stroke, given to the Universal Testing Machine for test assemblies with HLT-C2 and HLT-C3 specimens.

While the first test with HLT-C1 specimens progressed very well, due to short arms (beams) of the test assembly, the connections behaved in a 'mixed mode,' a combination of 'bending mode' and 'shear mode.' Since due to the limitation on the length of the UTM bench, the length of the beams could not be increased, the tendency of the specimens to behave in shear mode had to be somehow suppressed. This was done by adding a vertical tube with a limited length at the middle of each specimen unit (Fig. 5). Such vertical tube, due to its high shear stiffness, would prevent the connections from going through shear mode of deformation and would force them to just deform in bending. However, due to its short length and its location within the connection it would not add to the bending resistance of the connection substantially.

Figs. 8, 9 and 10 depict the first test assembly, with HLTC1 specimens, before the test, at its utmost upper position before failing, and at its utmost lower position before failing, respectively. The same sequence of events is depicted in Figs. 11, 12 and 13 for the second test assembly with specimens 5 HLT-C2, and in Figs. 14, 15 and 16 for the third test assembly with specimens HLT-C3.

The 'raw' hysteresis loops of HLT-C1 connections are shown in Fig. 17, with the tensile and compressive parts being separated from each other on the horizontal (rotation) axis. This was due to the total 'slack' in the whole assembly comprising the gaps between bolt holes and bolt shanks, the pin and the stub column, and in particular those between the pins of the two side beam supports and slots in the side beams. To have a better idea of how exactly the connections had performed under cyclic loading, these slacks which had polluted the loops, had to be removed. Fig. 18 depicts the 'modified' hysteresis loops of HLT-C1, without the effects of such slacks. The 'raw' and 'modified' hysteresis loops of HLT-C2 are presented in Figs. 19 and 20, respectively, while those of HLT-C3 are depicted in figs. 21 and 22.

Figure 8- First test assembly, with HLT-C1 specimens, before the test.

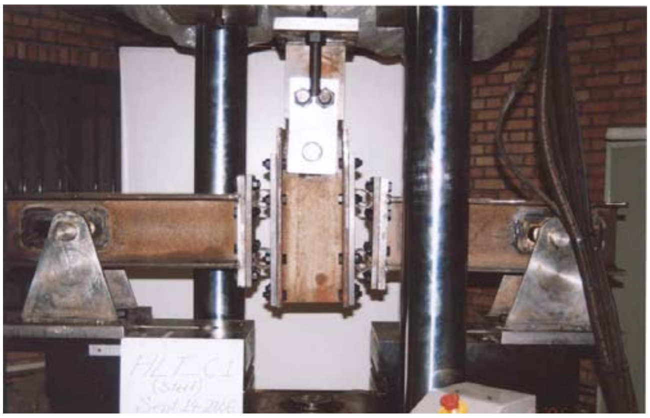

Figure 9- First test assembly, with HLT-C1 specimens, at its utmost upper position, before failure.

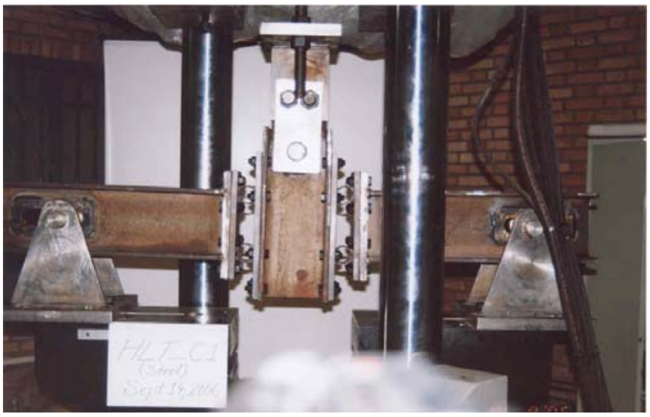

Figure 10- First test assembly, with HLT-C1 specimens, at its utmost lower position, before failure.

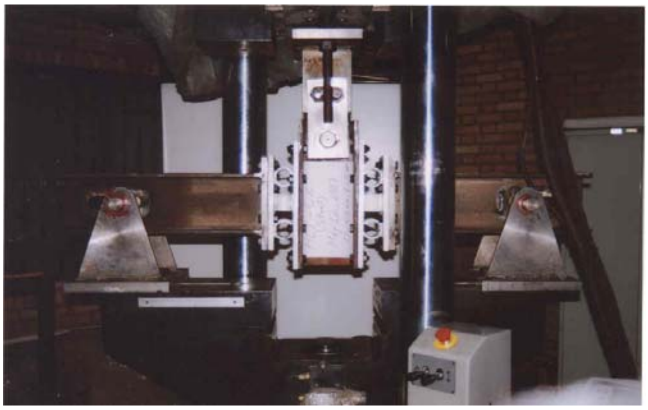

Figure 11- Second test assembly, with HLT-C2 specimens, before the test.

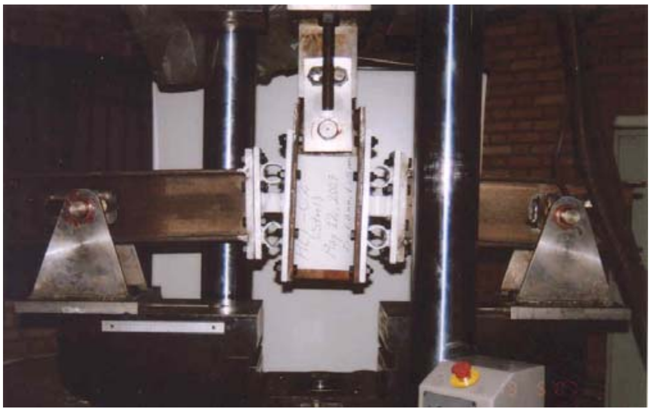

Figure 12- Second test assembly, with HLT-C2 specimens, at its utmost upper position, before failure.

Figure 13- Second test assembly, with HLT-C2 specimens, at its utmost lower position, before failure.

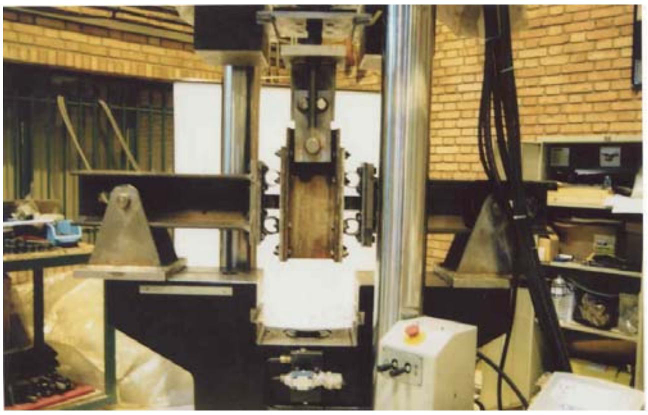

Figure 14- Third test assembly, with HLT-C3 specimens, before the test.

Figure 15- Third test assembly, with HLT-C3 specimens, at its utmost upper position, before failure.

Figure 16- Third test assembly, with HLT-C3 specimens, at its utmost lower position, before failure.

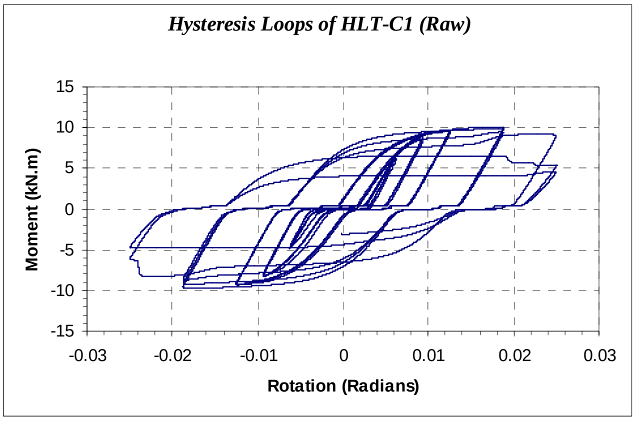

Figure 17- The 'raw' hysteresis loops of an 'average' connection of the first test assembly, HLT-C1.

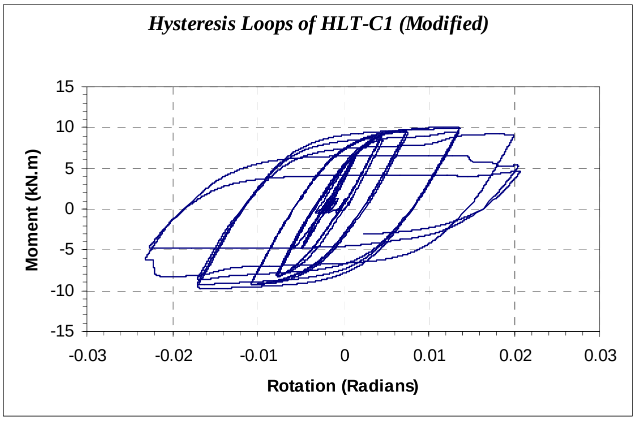

Figure 18- The 'modified' hysteresis loops of an 'average' connection of the first test assembly, HLT-C1.

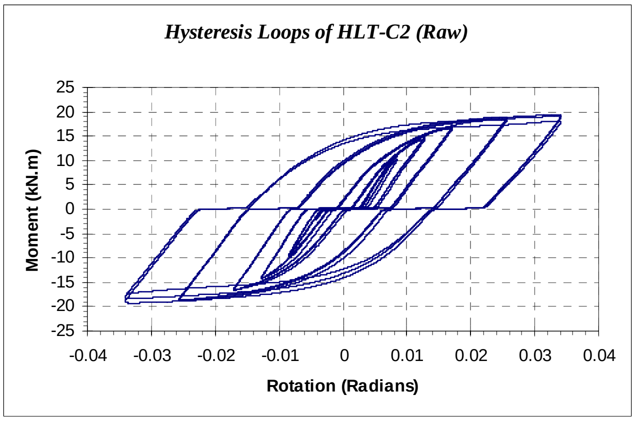

Figure 19- The 'raw' hysteresis loops of an 'average' connection of the second test assembly, HLT-C2.

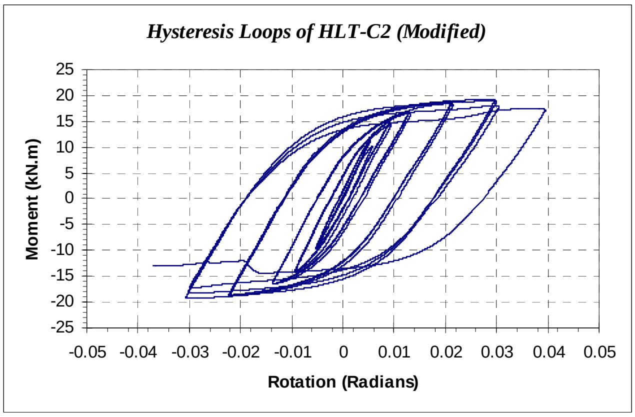

Figure 20- The 'modified' hysteresis loops of an 'average' connection of the second test assembly, HLT-C2.

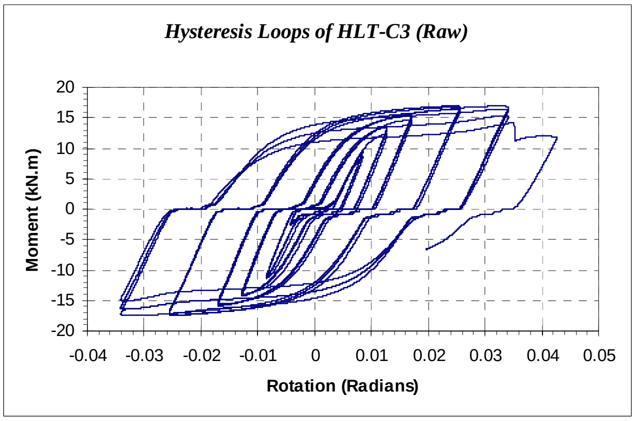

Figure 21- The 'raw' hysteresis loops of an 'average' connection of the third test assembly, HLT-C3.

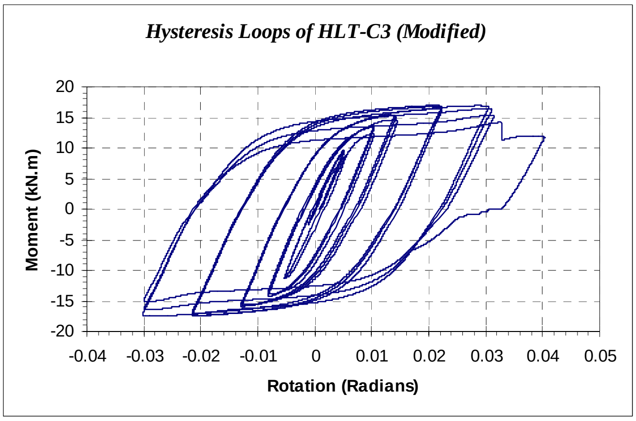

Figure 22- The 'modified' hysteresis loops of an 'average' connection of the third test assembly, HLT-C3.

In order to have a quantitative measure of the performance of this connection under cyclic loading regime, the amount of dissipated energy in each cycle, in each stage of loading, and, eventually, in the whole history of loading of each connection was worked out for each specimen and are shown in Tables 4, 5 and 6 for specimens HLT-C1, HLT-C2 and HLT-C3, respectively.

4. DISCUSSION

The flexural hysteresis loops of the specimens of the three tested assemblies clearly show the ability of the devised connection in absorbing and dissipating energy when subjected to an overload. It is true that under monotonic loading the connection had already sustained rotations up to 0.15 radians (Khonsari *et al.* (2001, 2002, 2003)), however, the degradation characteristics of cyclic loading regimes, already observed in many circumstances and reported by various investigators, has forced the authorities to set values at the range of 0.03 radians as the limit for a connection to sustain under cyclic loading. With regard to the tests reported here, the specimens of the second and the third assemblies, HLT-C2 and HLT-C3, apparently, reached this limiting value after being subjected to an adequate number of cycles. Though, with regard to the specimens of the first test assembly, HLT-C1, as it was well-observed during the test, and based on the experience obtained during testing similar specimens under shear loading (Khonsari *et al.* (2004)), due to susceptibility of the system to shear deformation (the two side beams were quite short), as explained earlier, the specimens responded with a mixed mode, flexural mode and shear mode, with the latter dominating the behaviour. Therefore, it is not surprising that the first series of specimens, HLT-C1, did not reach the limiting value of 0.03 radians. As far as the dissipated energy in various cycles of the loading of each specimen is concerned, as it can be seen in Tables 4, 5 and 6, it is quite substantial. This, apparently, will allow the designers to use this connection as a focal point for energy dissipation within the structure.

Table 4- The energy dissipation characteristics of one of the HLT-C1 specimens used in the first test assembly (without the middle vertical tube and D_{out} = 48.3 mm & t =3.25 mm).

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	0.38	1.45	0.24	0.37
	2	0.32			
	3	0.19			
	4	0.18			
	5	0.21			
	6	0.17			
2	1	7.47	14.75	4.92	7.62
	2	3.96			
	3	3.32			
3	1	43.88	128.00	42.67	66.13
	2	43.42			
	3	40.70			
4	1	112.92	367.46	122.49	189.82
	2	128.58			
	3	125.96			
5	1	296.11	939.49	313.16	485.31
	2	334.79			
	3	308.59			
6	1	429.47	959.12	319.71	495.46
	2	359.10			
	3	170.55			
7	1	n/a	n/a	n/a	n/a
	2	n/a			
	3	n/a			
Total Dissipated Energy			2410.27	n/a	n/a

Table 1- The energy dissipation characteristics of one of the HLT-C2 specimens used in the second test assembly (with the middle vertical tube and D_{out} = 60 mm & t = 5 mm).

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	0.47	1.51	0.25	0.61
	2	0.22			
	3	0.21			
	4	0.21			
	5	0.21			
	6	0.19			
2	1	21.83	43.18	14.39	35.34
	2	11.60			
	3	9.75			
3	1	85.39	245.25	81.75	200.79
	2	82.11			
	3	77.75			
4	1	215.27	607.60	202.53	497.43
	2	230.69			
	3	224.64			
5	1	608.87	1958.90	652.97	1603.76
	2	678.49			
	3	671.54			
6	1	1107.23	3421.22	1140.41	2800.96
	2	1194.60			
	3	1119.39			
7	1	1428.14	1428.14	1428.14	3507.65
	2	n/a			
	3	n/a			
Total Dissipated Energy			7768.8	n/a	n/a

5. APPLICATION

While in previous papers the application of this connection for repair and retrofitting aging offshore platforms was explained and details for fabricating special components to make such use viable was given, so far there has not been any indication of such use. However, with regard to onshore structures, at the time of writing this paper, the erection of the first structure in the world in which this connection is utilized is finished. The location of the building is Port of Asalouyeh in the Persian Gulf, near the South Pars Gas Field, which is an earthquake prone region. Fig. 23 depicts one of the steel frames of this building where KHONSAR™ connection is used to connect a beam to a column.

Table 6- The energy dissipation characteristics of one of the HLT-C3 specimens used in the third test assembly (with the middle vertical tube and Dout = 60 mm & t = 5 mm).

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	1.98	10.57	1.76	4.32
	2	2.21			
	3	1.77			
	4	1.55			
	5	1.55			
	6	1.51			
2	1	30.34	71.31	23.77	58.38
	2	21.68			
	3	19.29			
3	1	133.47	419.57	139.86	343.51
	2	147.77			
	3	138.33			
4	1	300.73	961.62	320.54	787.28
	2	335.61			
	3	325.28			
5	1	710.57	2304.52	768.17	1886.70
	2	809.35			
	3	784.60			
6	1	1169.72	3489.09	1163.03	2856.51
	2	1213.44			
	3	1105.93			
7	1	657.73	657.73	657.73	1615.45
	2	n/a			
	3	n/a			
Total Dissipated Energy			7914.41	n/a	n/a

Figure 23- A real application of KHONSAR™ connection, during the course of installation of the structure.

CONCLUSIONS

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

1. The flexural behaviour of the HLT version of the devised connection under cyclic loading proved to be quite satisfactory, reaching the critical value of 0.03 radians which would establish it as 'qualified' according to the

criteria devised by AISC. It should be added that, as reported in previous papers, under monotonic loading, rotations up to 0.15 radians were easily obtained. Such values do not seem to have been reported from tests on other types of connections.

2. If the conditions of the system in which the connection is used is such that it does not enter into shear mode, i.e. it is used to connect a long-enough beam to a column, as was the case for the second and the third specimens, it is expected to reach the critical value of 0.03 radians.
3. With regard to circumstances where the connection is used to connect a short beam to a column, as was the case for the connections of the first test assembly, it behaves in mixed mode, a combination of flexural mode and shear mode, and may not perform as efficiently as it would in the absence of shear deformations.
4. It is expected to obtain better test results, hence better performance under cyclic flexural loading, if the welding of the connections is done by more qualified welders. This is due to the general fact that welded components are more sensitive to cyclic loading.

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