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INNOVATIVE STRUCTURAL JOINT TO INCREASE SAFETY DURING EARTHQUAKES

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SUMMARY

A new beam-to-column (as well as bracing-to-frame) connection has been developed. This new joint, called KHONSAR,™ is a separate self-contained structural component with a specific geometry designed to allow rotations to develop far beyond those of joints developed and used so far. In its simplest form the new component comprises two parallel attachment plates, between which two or more cylindrical tubes are attached, either in a parallel or in a perpendicular relation to the axis of bending. This unit can be housed in an annealing oven to eliminate the adverse effects of welding (used to join the tubes and the attachment plates), such as material embrittlement, and restore its ductility. The attachment plates of the connection are then connected to the beam and the column by non-destructive fasteners. Tests carried out to date on the two versions of the connection under *'bending'* and *'shear'* have established the importance and effectiveness of annealing to restore material ductility following fabrication. The tests confirmed that the new connection has the ability to accommodate large rotations; at least six times the capacity of existing semi-rigid connections. Moreover, they showed the great shear deformation capacity and strength of the joint. Finally, the use of the new connection enables engineers to design the joint independently for the desired *stiffness, strength,* and *rotational capacity,* thus overcoming the current design dilemma caused by the interdependence between these parameters in conventional joint design.

INTRODUCTION

The high rotational demand of structural joints during earthquakes is not fulfilled by currently used joints. The rotational capacity of currently used beam-to-column joints is limited to about 0.025 radians (see Nethercot [1] for a review of test results on beam-to-column joints). Joint geometries prevent the development of large rotations. Rotational capacity is often reduced further by the *'embrittlement'* effects of fabrication processes such as *'flame-cutting'* and/or *'welding.'* Moreover, increasing the rotational capacity of conventional joints always conflicts with the required 'stiffness' and the 'strength' of the joint. This is a dilemma encountered by structural engineers. Amongst all existing joints, to the best of authors'

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knowledge, there does not exist any joint with high rotational capacity, and at the same time high rigidity and strength. Nor, does any with high rigidity and strength, and at the same time high rotational capacity. While moment frames with adequately strong beam-to-column connections are believed to have the best performance during earthquakes, such frames without flexible-enough joints to satisfy the great rotational demand of the structure at joints during severe earthquakes, may receive tremendous damage, as they did during Northridge earthquake and other previous ones (see Bruneau [2]). Therefore, it is the combination of these three factors which is needed to guarantee the desired performance of the structure during an earthquake, and exiting joints with the following relation between their major characteristics are not suitable for building frames built in earthquake-prone areas.

$$\text{Stiffness and/or Strength} \neq \text{Rotational Capacity}$$

Structural frames made of brittle materials such as concrete present different problems. These structures lack any inherent material *'ductility'* to create favorable performance in earthquake-prone regions. It is therefore necessary to engineer ductility into the structure at selected focal points. The most important and apparent outcome of such increased ductility is a reduction in the frequencies of vibration of the structure, hence the attenuation of earthquake-induced forces in it.

Using the *'weak-beam—strong-column'* concept forces the plastic hinges to form inside the beam, and leads to the necessity of beam *'replacement'* after an earthquake. The same outcome exists for beams of eccentrically-braced frames (EBFs) to which brace elements are connected. Such replacements, though possible, are neither simple nor economical. The alternative, column replacement, is highly expensive and sometimes is not viable at all. Therefore, a new approach seems to be required, that of making the joint replaceable? Such replaceability is less costly provided joint works in a *'sacrificial'* capacity and is designed to '*attract'* and '*contain'* the overload damage.

Taking this fact into account that during any overload, most of the times, the connections are at the forefront of receiving damage, it is not wrong if it is claimed that the destiny of structures is determined by their connections. Having accepted this, in order to reduce the cost of aftermath repair, it is beneficial to design the connections to be replaceable. Regarding the fact that to replace a damaged beam involves a great amount of effort and cost, also that of a column, if ever possible, is much more difficult and costly, now that the connection is to be replaceable, it is better to prevent the damage from spreading into the beam and the column and contain the damage by the connection, hence forcing the connection to work in a sacrificial capacity. And, if so, then it should be the connection which has to have the task of energy dissipation. This means that they have to have a high energy dissipation capacity. Commonly used connections, due to their restrictive geometry, cannot deform as such, without experiencing failure. So, of the two contributing factors towards energy dissipation, namely large distortions and material yielding, the former has normally a marginal role while the latter, however, is impaired and reduced if the fabrication of the connection involves welding. The solution to these two problems is i) to use a non-restrictive geometry which allows the joint to undergo large distortions, and ii) to either avoid practicing operations which may degrade the ductility of the material, welding etc., or if so, restore the ductility by subjecting the connection to a desirable thermal cycle, annealing etc. To anneal a metallic entity is not easily possible unless the welded parts are of limited size so that they can be housed in the annealing oven. Therefore, if the connection, which may somehow involve welding, is a self-contained separate entity, hence of a limited size, it can be annealed in an oven to restore its ductility before it is connected to the beam and the column with non-destructive fasteners, bolts and nuts. Such connection, then, can have a high enough energy dissipation capacity to be eligible for having the role of energy dissipator in the structure.

With all of the above considerations in mind, a new beam-to-column connection was developed and patented. Several tests were carried out on the two versions of this connection, described below, and its components. Bending tests proved its ability to rotate substantially and dissipate large amount of energy in an efficient manner (with high energy dissipation per unit weight of material used). Shear tests, on the other hand, proved its ability to undergo large shear deformations while at the same time having much shear strength.

THE NEW CONNECTION

The new connection, called KHONSAR,™ is a separate entity which attaches a beam to a column by non-destructive fasteners, i.e. bolts and nuts. This removes the chance of development of brittle zones within the material of the column and the beam at the connection. Fabrication of the connection may involve welding or extrusion. In either case, residual fabrication stresses can be relieved by suitable heat treatment. Moreover, if the ductility of the joint is degraded during fabrication, say as a result of welding, through such process (heat treatment) it can be restored. The pre-fabricated connection comprises two stiff attachment plates which are attached to the beam and the column. In addition to these plates, at least two energy-dissipating members are used in this connection which are positioned in two opposite zones of the connection in a manner that upon bending of the connection, one energy-dissipating element is subjected to tension, the one in front of the tensile flange of the beam, and the other is subjected to compression, that in front of the compressive flange. As very efficient energy-dissipating elements, circular or other types of hollow tubular sections, under diametral loading, tensile or compressive, are employed.

In general, two different configurations for laying the energy-dissipating elements between the two attachment plates are conceived. In its *'original'* form (version), the two tubular sections are laid between the plates in a parallel relation to the axis of bending. This arrangement can be further enriched in *'shear'* by adding a real hinge between the two tubes for circumstances where the shear transfer capacity of the two tubes proves to be inadequate, although recent shear tests on specimens of this version proved the ability of this configuration to sustain great shear forces. Fig. 1 illustrates this version. However, as an *'alternative'* to this 'original' version, in another embodiment, the two tubes are laid between the attachment plates in an orthogonal relation to the axis of bending. This version can be simplified by using one single tube to cover both tensile and compressive tubes, running along the height of the connection. This version is illustrated in Fig. 2. Moreover, this version can be further strengthened by employing several, two or more, parallel vertical continuous tubes.

An interesting feature of this connection is that while for bending about one axis it acts as one of the above-mentioned versions, about the other axis of bending, it will act as the other version, if the joint is subjected to bi-axial bending. Another feature, discussed previously [3-5], is the ability of the joint to deliver the desired rotation and strength independently, unlike most other joints currently in use. As already mentioned, with conventional joints, large rotations cannot be achieved unless the stiffness and the strength are reduced, and vice versa.

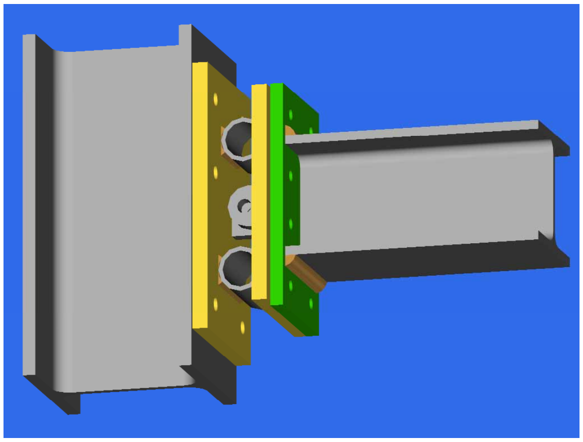

Figure 1. The 'original' version of KHONSAR™ with the two energy-dissipating elements, tubes, laid parallel with the axis of rotation (Horizontally-Laid-Tubes, HLT, version). The middle hinge is optional.

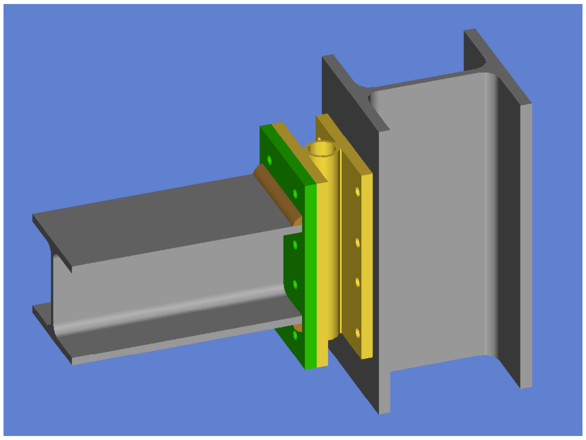

Figure 2. The 'alternate' version of KHONSAR™ with the tube(s) laid perpendicular to the axis of rotation (Vertically-Laid-Tubes, VLT, version). In this example the entire connection is extruded in aluminium.

Finally, because the connection is a separate entity, there is no limitation on the type of elements to be connected. Thus, beams and columns of any material can be attached to each other by this joint. For instance, if appropriate, steel beams can be connected to concrete columns by this joint with ease.

THE EXPERIMENTAL WORK

In order to assess the behaviour and performance of the devised connection experimentally, a fairly comprehensive programme was arranged and conducted. This programme consisted of tests on single circular tubes welded to two parallel plates, as constituting elements of the connection, as well as on connection units. The former series of the tests were intended to provide the authors with the required information on the behaviour of circular cylindrical tubes, as they are utilized in the connection, i.e. welded to two attachment plates, loaded under diametral tension or compression. Tests on these series were of an appreciable number and under various types of conditions, namely 'un-annealed' and 'annealed.' As expected, these tests revealed quite clearly the effectiveness of annealing in removing the adverse effects of welding, in particular the embrittlement of the heat affected zones (HAZs) and the potential for future development of cracks. The results of the initial stages of this part of the programme have already been published [6], while the complete outcome of this part is to be published in due course.

The experimental work conducted on the connection units can be categorized into two major following types.

1. Tests to evaluate the *'bending'* characteristics of the joint.
   - Bending tests on the HLT version specimens of the joint, HLT1 and HLT2.
   - Bending tests on the VLT version of the joint, VLT1 and VLT2.
2. Tests to evaluate the *'shear'* characteristics of the joint.
   - Shear tests on the HLT version specimens of the joint, HLT-V1, HLT-V1-2 & HLT-V3.
   - Shear tests on the VLT version specimens of the joint (to be carried out in due course).

All of the above tests were of *'monotonic quasi-static'* nature.

Bending Tests

As far as bending tests on the connection specimens are concerned, limited amount of work has been done so far. This comprises two series of tests on specimens of horizontally-laid-tubes (HLT) version, reported previously [3-5], and two series on vertically-laid-tubes (VLT) version, carried out more recently, one already reported [5] and one to be reported here. However, for the sake of comparison, the results of tests on another type of connection, namely 'endplate' type, carried out by others [7], are reported as well. All of the tested specimens of KHONSAR™ type were of mild steel, which were 'annealed' after fabrication and prior to fastening to the column and the side-beams. The annealing process comprised the gradual heating of the specimen in an annealing oven up to 650° C, retaining it in this temperature for 1 hour and then allowing it to cool in the oven overnight. Since the tubes used to fabricate HLT and VLT specimens were different, their sizes are compared in Table 1. The producer of the tube of the larger diameter, used in VLT1, VLT2, and HLT-V3 specimens, had already ensured the authors of the type of the material of the tube, *viz.* mild steel. Regarding the tube of smaller diameter, used in HLT1, HLT2, HLT-V1, and HLT-V1-2 specimens, since it was acquired off the shelf, though believed to be made of mild steel, such assurance did not exist. Despite this, during tests carried out on several tensile and compressive specimens fabricated of this type of tube, they showed a very high degree of ductility to confirm the above notion with a good degree of certainty [6].

Table 1. Sizes of the tubes employed in various bending and shear specimens.

Specimen	Tube Outside Diameter (mm)	Tube Thickness (mm)	No. of Tubes	Tubes Length (mm)
HLT1	43.4	4.2	2	60 & 80
HLT2	43.4	4.2	2	60 & 80
VLT1	48.3	3.25	1	160
VLT2	48.3	3.25	2	160 & 160
HLT-V1	43.4	4.2	2	80 & 80
HLT-V1-2	43.4	4.2	2	80 & 80
HLT-V3	48.3	3.25	2	80 & 80

Fig. 3 depicts the geometry of the tested specimens of the HLT version, while those of the VLT specimens are shown in Figs. 4 & 5. In order to test such connections, a T-shaped test assembly was used [5]. However, to substantially simplify the measurements and the calculations which would lead to the moment-rotation curve of the specimens, the main outcome of the test, an innovative idea was devised and used by the authors. Since the vertical displacement of the column in this assembly normally arises from at least two sources, namely the rotation at the connection and the bending of the side beams, by greatly increasing the rigidity of the beams, the effects of the latter are removed. However, there may be other sources which may contribute to this vertical displacement, namely the extension of the bolts, the bending of the flanges of the column, and the bending of the endplates of the beams, necessary to be fastened to the attachment plates of the connection units. In all the tests, the effects of all of these possible sources were eliminated by using over-stiff elements. For the details of the calculations made for obtaining the moment-rotation curves of the tested specimens, the reference [5] can be consulted. Through such calculations, the *'average'* moment-rotation curve of the specimens of each test assembly was obtained (see Fig. 6)—since in each test two 'nominally' identical specimens are tested at the same time, the resulting curve represents the average values of the moment and rotation of the two simultaneously-tested connection units.

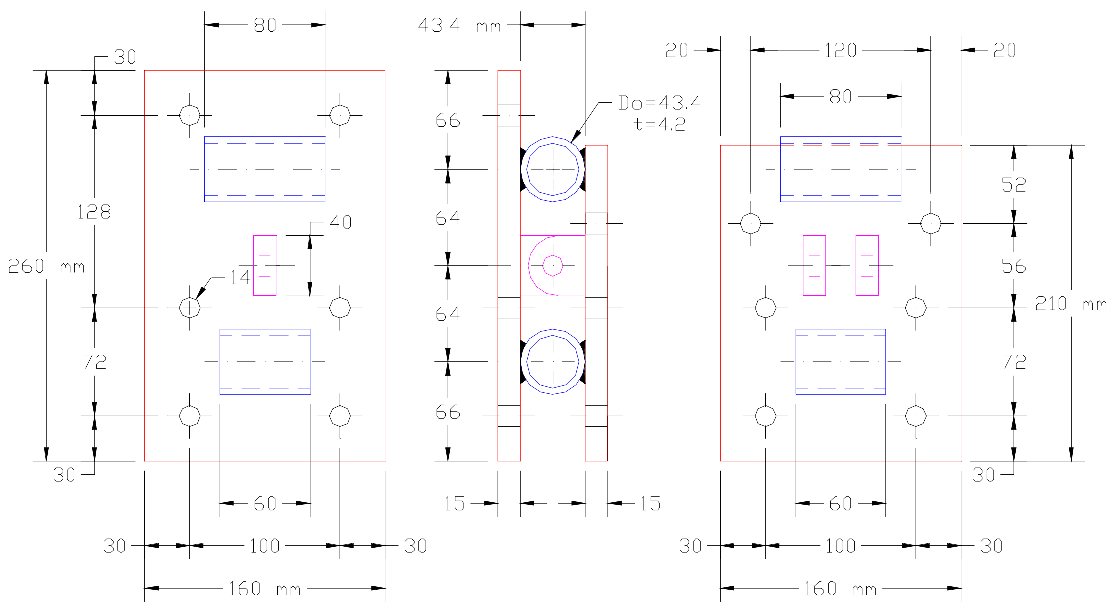

Figure 3. Details of the tested connections of the Horizontally-Laid-Tubes (HLT) version of KHONSAR.™

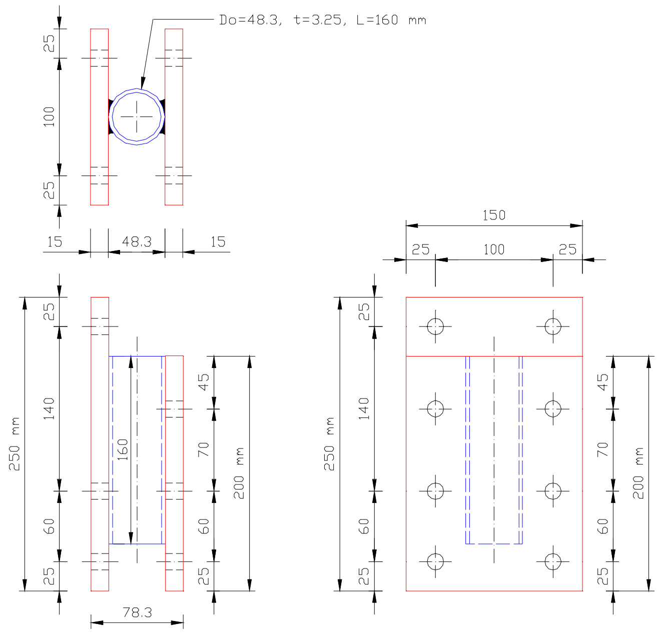

Figure 4. Details of the tested connections of the first Vertically-Laid-Tubes (VLT) series of KHONSAR™ in which one vertical tube was used, VLT1.

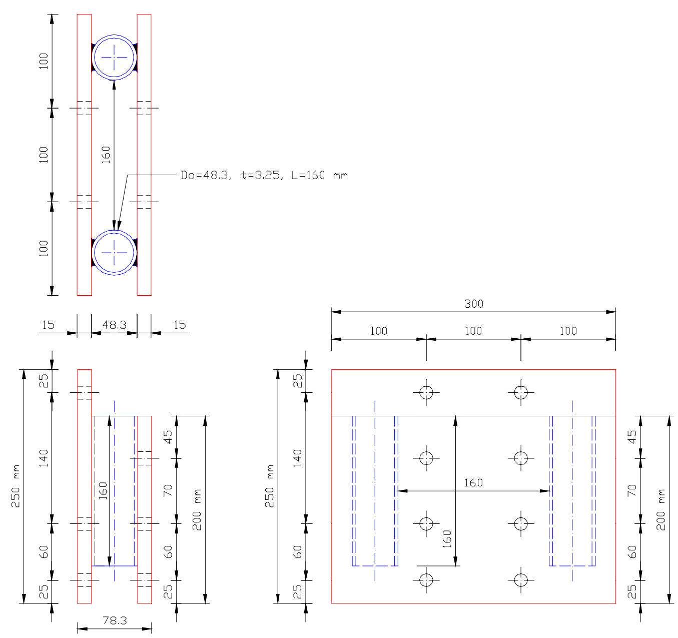

Figure 5. Details of the tested connections of the second Vertically-Laid-Tubes (VLT) series of KHONSAR™ in which two vertical tubes was used, VLT2.

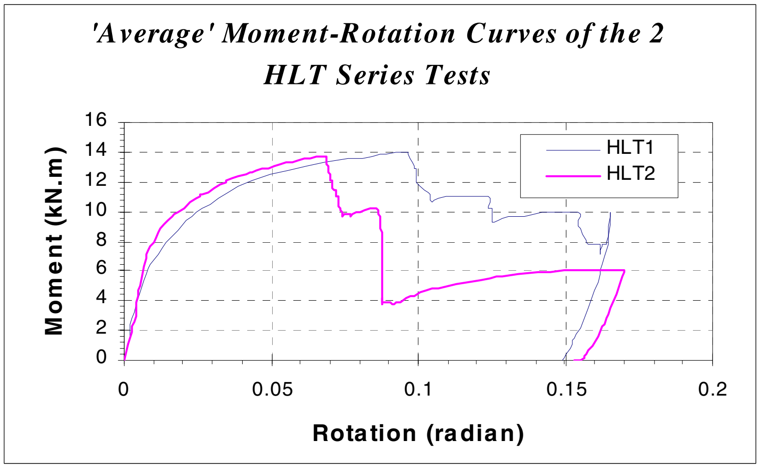

Figure 6. Average moment-rotation curves of the two series of tests on Horizontally-Laid-Tubes (HLT) connections.

As far as the tests on VLT specimens are concerned, again, a very similar over-stiff T-shaped test assembly was used. Using the same logics as those given for the HLT test assemblies [5], identical transformation formulae were obtained through which the load-displacement curves for the tip of the columns of the two test assemblies were transformed to the *'average'* moment-rotation curves of the two series of VLT specimens (see Fig. 7).

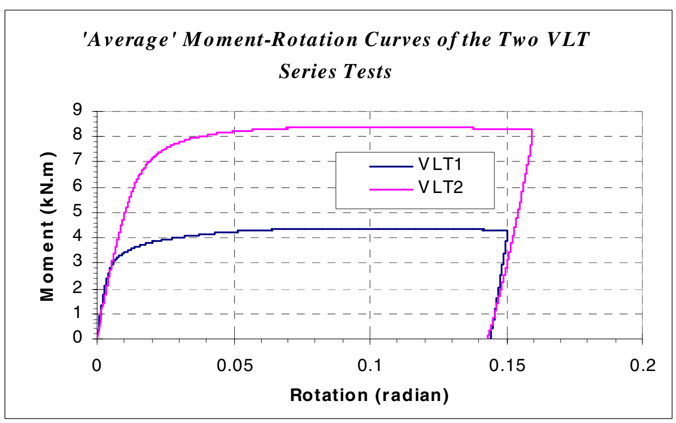

Figure 7. Average moment-rotation curves of the two series of tests on Vertically-Laid-Tubes (VLT) connections.

The results of all the bending tests carried out so far, on the two versions of KHONSAR™ connection, together with those for a more conventional connection of the 'endplate type,' carried out by Jenkins *et al.* [7], are reported and compared in Table 2. 'Test 3' and 'Test 5' specimens of reference [7] were both of the *'Flush Endplate'* type. That of 'Test 3,' was composed of an end-plate, 340×200×12 mm^3, connecting a 254×254UC132 column to a 305×165UB54 beam (these profiles are in compliance with the British Standards) by 6 M20, grade 8.8 bolts, 4 in tension and 2 in compression. The 'Test 5' connection, however, was composed of an end-plate of 340×200×25 mm^3, connecting a beam and a column identical to those of 'Test 3,' through the same number of bolts of the same type and size. The results reported in Table 2 are the maximum moment, maximum rotation, and the dissipated energy of each connection unit. Those of Jenkins *et al.* were derived by the authors using the moment-rotation curves given in their paper

[7]. Photographs of the test assemblies used for testing HLT and VLT connections are shown in Figs. 8 & 9, while that of the deformed VLT2 specimen is depicted in Figs. 10, proving the absence of any developed *'cracks'* despite the severity of distortions of tubes.

Table 2. Comparison data for four KHONSAR™ connections and two end-plate connections of Jenkins (J.) *et al.* [7].

Test No.	Max. Rotation (radian)	Max. Moment (kN.m)	Dissipated Energy (J, N.m)
HLT1	0.1489	14.0	1714
HLT2	0.1532	13.7	1346
VLT1	0.1502	4.2	607
VLT2	0.1595	8.4	1178
Test 3 (J. *et al.*)	0.0249	93.5	1551
Test 5 (J. *et al.*)	0.0266	165.0	3059

Figure 8. Photograph of the test assembly of the second HLT series, HLT2.

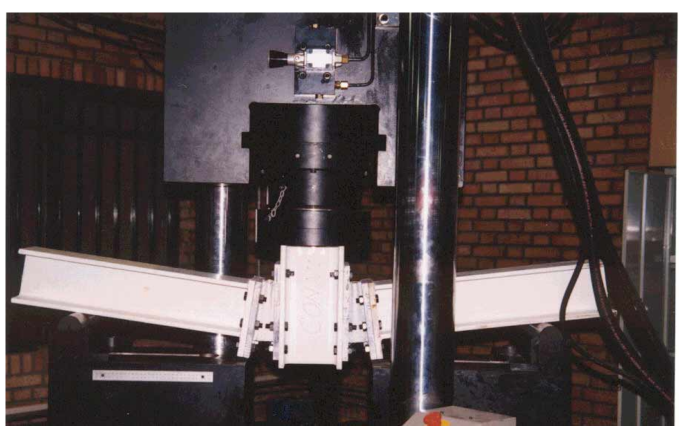

Figure 9. Photograph of the test assembly of the first VLT series, VLT1.

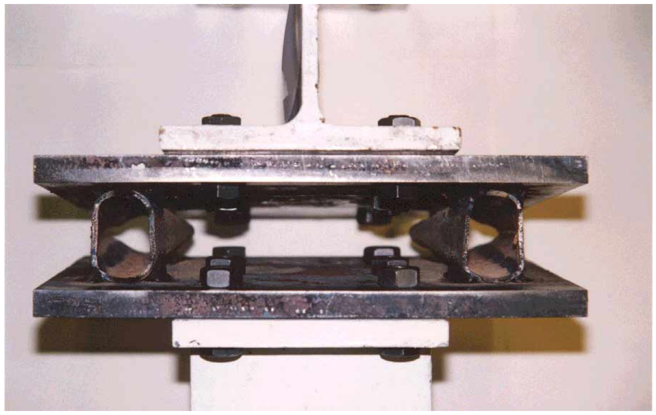

Figure 10. Photograph of the deformed shape of one of the VLT2 specimens, showing the absence of any cracks despite the severity of distortions of the tubes.

Shear Tests

In order to assess the shear characteristics of the horizontally-laid-tubes (HLT) version of the connection, which was initially conceived by the authors of not being adequate, a series of tests were carried out on this type of connection. However, with regard to the vertically-laid-tubes (VLT) version of KHONSAR,™ such inadequacy was not conceived though it has not been substantiated yet. Due to the special configuration of this version of the joint, a special test assembly had to be designed first. Such assembly had to be consistent with the geometry and the response of the specimen to shear forces, while preventing it from undergoing bending. Fig. 11 shows the details of such test assembly with specimens having tubes of 43.4 mm outside diameter, 4.2 mm thickness and 80 mm length, the same as those used in the two HLT bending specimens (see Fig. 3). In each test two connection units are tested at the same time.

Altogether, 3 tests of this type were conducted on double-shear-specimen test assemblies. In the first two, tubes of the smaller size were employed whereas in the third, tubes of the larger size were used (see Table 1). However, the first test (HLT-V1) was not fruitful since at very early stages of the test the pin, used to connect the pulling plate to the two attached (bolted) specimens, bent and proved to be structurally inadequate. Therefore, its diameter was increased from 30 mm to 45 mm.

Having changed the deformed pin with the one with larger diameter, the second test of this type was conducted on the same previous specimens, HLT-V1, this time called HLT-V1-2, assuming that the distortions of the tube have been predominantly of *'elastic'* nature. This test went on quite successfully. However, at later stages of the test, due to unavoidable imperfections existing in the specimens, the response of the assembly started to become unsymmetrical. Fig. 12 depicts the deformed shape of this assembly at a fairly early stage of the test, demonstrating the huge potential of this connection to deform under shear, something that none of the existing beam-to-column joints possesses. This happened while the shear strength of the specimens also proved to be far above what was initially expected by the authors. One simple justification for this is the bending of the 30 mm pin of the assembly at early stages of the first test. However, the *'average'* shear-force—shear-displacement curves of each connection unit of the two assemblies are depicted in Fig. 13.

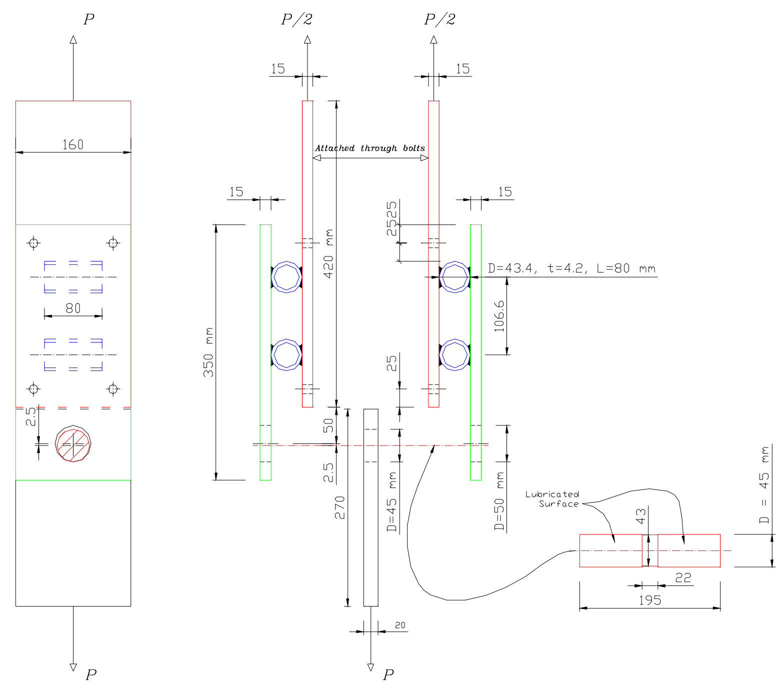

Figure 11. The shear test assembly used for testing two connection units at the same time.

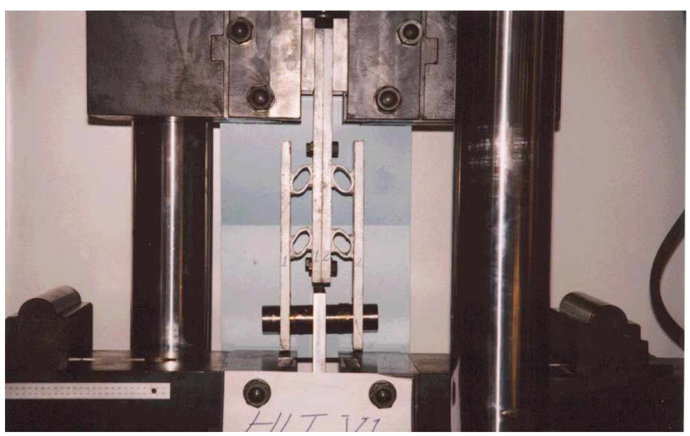

Figure 12. The deformed shape of the second assembly, with HLT-V1-2 specimens, at a fairly early stage of the test.

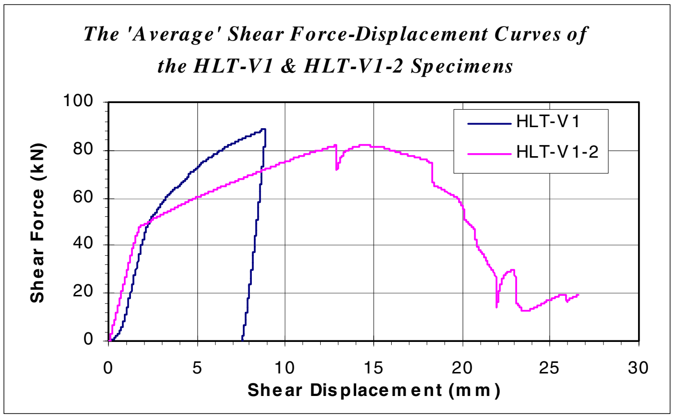

Figure 13. The 'average' shear force-displacement curve of either of the two Horizontally-Laid-Tubes (HLT) connections of the second series (HLT-V1-2).

In addition to the two series of shear tests, one on *'virgin'* specimens and the other on *'slightly deformed'* specimens, another series of shear tests was also carried out. This new series involved specimens very similar to the previous ones but with tubes of different sizes, HLT-V3 series (see Table 1). Moreover, the material of the tubes of these specimens was *'definitely'* mild steel, since they were directly acquired from the producer, whereas that of the HLT-V1 or HLT-V1-2 was *'believed'* to be mild steel, since it was purchased off the shelf. The test on HLT-V3 specimens went on very well until the two comprising specimens of the test assembly underwent very large shear deformations (see Fig. 14), eventually leading to the disintegration of half of one of the specimens, which fell down and hit the cable of the controlling computer and cut its power. Therefore, despite the excellent performance of the specimens of this series, no recorded results for them are available.

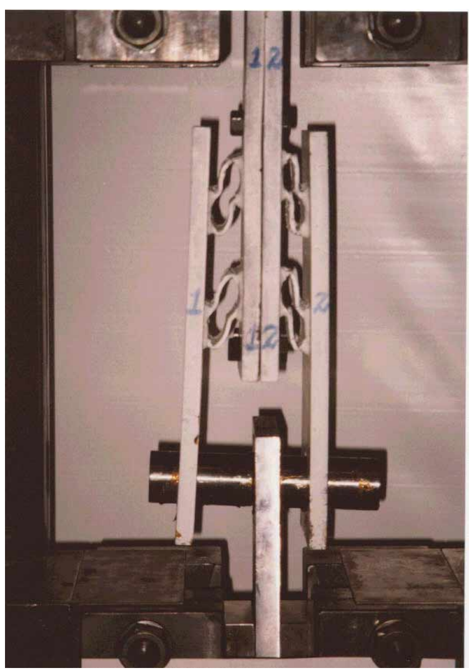

Figure 14. The deformed shape of the third assembly, with HLT-V3 specimens, at a very late stage of the test.

The absorbed and dissipated energy of the HLT-V1 and HLT-V1-2 specimens, together with their shear strength and maximum shear deformations, all as 'average' values of the two specimens, are compared in Table 3. Since as the specimens deform severely, the effects of inevitable imperfections start to affect the behaviour and performance of the specimens, leading to their unsymmetrical behaviour, the simplifying assumption of equal division of the total pulling force (recorded by the universal testing machine) between the two specimens as their shear resistance at any time (see Fig. 11) will lead to an *'average'* shear force, hence *'average'* dissipated energy by either constituting specimen of the test assembly. Since, to the best of knowledge of the authors, none of the existing beam-to-column joints have any appreciable amount of shear displacement, therefore, no comparison data for other types of joints have been added to Table 3.

Table 3. The maximum shear displacement and strength together with total dissipated energy of the two 'average' specimens of the two tests. HLT-V1 is the 'virgin' form of HLT-V1-2.

Specimen	Max. Shear Displacement (mm)	Shear Strength (kN)	Dissipated Energy (J, N.m)
HLT-V1	8.83	88.82	478.86
HLT-V1-2	26.56	82.00	1484.17
HLT-V3	Lost Data	Lost Data	Lost Data

DISCUSSION

Tables 2 & 3 together with Figs. 6, 7 & 13 describe in brief the major features of this newly devised connection. Its *'rotational capacity,'* also highlighted in previous papers [3-5], was, and still is, considered as one of the unique advantageous features of it. As Table 2 reveals, it is 6 times those of the endplate connections of Jenkins et al. [7], whose values are reasonably large compared with those of many other commonly used semi-rigid beam-to-column connections. Referring to the value of 0.03 radian, indicated by AISC [8] as the benchmark for qualifying a connection for being used in *'special moment frames,'* i.e. the most ductile moment frames, the ability of the geometry of the joint in delivering very large rotations becomes more evident. However, such amounts as 0.15 radian, observed during the tests reported here for either version of the joint, can be easily *'doubled'* or *'tripled'* by using two attached connection units at the same time to join a beam to a column. This versatility will highly reduce the chance of joint failure as a result of a high rotational 'demand' at the joint by the structure during any violent and savage overload, earthquake, blast, or, if the worst comes to the worst, during rare circumstances where the combination of such loadings affect the structure, e.g. gas explosion during an earthquake.

Regarding the other important and unique feature of the HLT version of this joint, namely its combination of *'very large shear strength'* and *'very large shear deformation capacity,'* which is not provided by any other existing connection known to the authors, it can be well exploited in circumstances where there is a chance for impact of dropped objects on decks (slabs) supported by such connection, e.g. any part of the topside supporting the processing plants in an offshore platform, etc. Its ability to substantially deform under shear force and dissipate energy of such impact loadings can highly reduce the inflicted damage on the less replaceable parts of the structure, the constituting elements of the deck (slab), hence reducing the cost of repair, bearing in mind that the connection, itself, is *'replaceable'* and acts in a *'sacrificial'* capacity. Also, it can be exploited in circumstances where there is a chance of successive collapse of building floors onto one another, initiated as a result of collapse of an upper floor, caused by an explosion, etc., as it happened during the collapse of WTC buildings.

The departure of the second shear test assembly from symmetry may in fact be the result of not having involved *'virgin'* specimens, and the fact that its constituting specimens were already tested and had undergone some limited permanent deformations. However, a more realistic value for the dissipated energy of HLT-V1-2 is the sum of that obtained in the test on the virgin specimen (HLT-V1) and that of the pre-deformed one (HLT-V1-2), i.e.

$$478.86 + 1484.17 = 1963.03 \quad \text{J}$$

The non-smooth trend of the final parts of the shear force-displacement curve of the second shear specimens (HLT-V1-2) is in fact a direct consequence of the departure from symmetry, a consequence of inevitable existing random imperfections in the specimens.

Finally, for more detailed discussions on this joint, earlier publications [3-5] can be consulted.

CONCLUSIONS

Using the results of the bending and shear tests carried out on various HLT and VLT specimens of the devised connection, the following conclusions can be made.

1. High rotational demands for structural connections, e.g. beam-to-column joints, can be satisfied by using the new design. This is due to the *'unrestricted' geometry* of the connection.
2. Unlike almost all conventional joints, the new connection has the ability to be designed independently for the required moment as well as rotational capacity.
3. Being able to work in a *'sacrificial'* capacity, together with the ability to *'contain'* the damage, the connection can considerably reduce the propagation of damage to the beams and columns throughout the structure. Taking account of the *'replaceability'* of the connection makes the repair of the damaged structure viable and cost-effective.
4. As a separate *'self-contained'* package of limited size, the connection can be housed in a heat-treatment oven and subjected to the desired thermal cycle (e.g. annealing or tempering) to restore its ductility, degraded as a result of welding.
5. The use of this unrestricted geometry, together with the restored ductility, not only enables the joint to undergo *'large rotations'* without developing cracks, and thereby to guarantee an enhanced flexible response of the structure under violent and unpredictable loadings, but also enables it to absorb and dissipate large quantities of energy.
6. The stiffness, strength, rotational capacity, and the energy dissipation capacity of the connection can be adjusted to the demand of the structure by using cylindrical tubes of various shapes and sizes.
7. By filling the core of the connection unit (excluding the attachment plates) in a non-brittle fire-resistant agent, the tolerance of the joint, hence that of the structure, to fire is increased, reducing the vulnerability of the structure to fire.
8. The use of continuous tubes to cover both tension and compression zones, as in the vertically-laid-tubes version of the connection, has the advantage of reduced manufacturing costs, but at the expense of a greater material consumption.
9. The premature failure of the tensile tubes in the horizontally-laid-tubes specimens, and the resultant reduction in strength of the connection, was not observed in the test with vertically-laid-tubes, when both underwent comparable rotations. This may be due to the fact that the material of the tubes used in vertically-laid-tubes version of the joint was 'definitely' mild steel whereas that of the ones used in horizontally-laid-tubes version was 'believed' to be mild steel.
10. The great *'shear deformation capacity'* of the HLT version of the joint makes it a very good candidate for acting as the joining element of bracing systems to structural frames. In this way, the over-stiffening effects of various types of diagonal bracing system can be reduced, leading to

a softer, dynamically less vulnerable, structure which in turn reduces the earthquake-induced forces in the system.

11. The great shear deformation capacity of the HLT version of the joint can be well exploited if it is used as the joining element of various slabs/decks (elements) to their supports. In case of an explosion or any cause of an upper floor slab collapse, the lower floor slab, through the *shear resistance* and *shear deformation capacity* of its KHONSAR™ supports, can tolerate the shear overload, preventing the process of chain collapse of successive floors onto the lower ones.

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