Experimental Investigation into the Behaviour of a Beam-to-Column Connection with Improved Initial Stiffness

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SUMMARY:
A newly devised beam-to-column connection whose specimens were already subjected to monotonic and cyclic bending loadings (in previous tests) was further studied. Since in previous studies it had shown limited Initial (Elastic) stiffness which could prove insufficient in some circumstances, in the current work specimens similar to those of previous tests were modified by filling its components (tubes) with a lightweight concrete manufactured with Expanded Perlite Aggregates (EPA). Monotonic tests carried out on these specimens showed a fair improvement in the initial stiffness of all specimens. Moreover, the dissipated energy of the tested specimens under monotonic loading increased substantially.

Keywords: Semi-Rigid Connections, Monotonic Loading, Energy Absorption and Dissipation, Perlite Concrete

1. INTRODUCTION

Steel structures, due to their potential in providing sufficient ductility against lateral loads, particularly during earthquakes, have always been considered by structural designers. Apparently, exploiting this potential requires a proper design, which is feasible by recognition of the actual behaviour of structural components. Meanwhile, steel connections, as structural components, play a significant role in the overall behaviour and stability of the structure under lateral loads. Many configurations of steel connections have been proposed so far, verifying the importance of this structural component. Serious efforts were made by many researchers to achieve a perfect configuration.

In the process of designing steel structures, in order to simplify the definition of various connections, the connections are divided into two main categories; rigid joints and pin joints. The advent of computers, allowing more precise analysis of structures and connections, on one hand, and the emerge of the idea of semi-rigid connections because of its economical benefits, on the other, promoted more studies on the benefits and limitations of semi-rigid connections.

During an earthquake, rigid connections, in spite of absorbing more load, have less displacement than semi-rigid ones. Therefore Semi-rigid connections would be highly desirable, considering the condition that the relative displacement of the structure does not exceed its limit. Furthermore, semi-rigid connections have another favourable feature which is their ability to distribute the moment through the connected members in an optimized manner. This type of connection, distributes the moment of gravity forces to the beam in a way that the beam has to be designed for less moment. Therefore, the consumption of material to make the beam will be optimized. It should be noted that in simple (pin) and rigid connections, the maximum strength is not reached in most of the points throughout the beam.

2. PERLITE CONCRETE AND ITS APPLICATION IN PROMOTING THE BEHAVIOUR OF THE INNOVATIVE CONNECTION

In order to increase the stiffness of tubes under diagonal loading, they can be filled with some materials as fillers. The previous experimental studies on the devised connection showed that the connection has low initial stiffness, so it enters the nonlinear phase very soon. Delaying the commencement of the inelastic behaviour of the connection was possible through increasing the initial stiffness, though it should be done in a way that the desired energy absorption characteristics of the connection remain safe. In this regard, it was decided to use the foam-filling concept for the tubes which were used in the connection; therefore they were filled with Perlite concrete. The application of Perlite concrete in the connection was due to the specific characteristics of the Perlite which is used in this type of concrete. The Perlite concrete has a low elastic modulus, which is desired in the purpose of this study.

2.1. The Primary Experimental Studies

These experimental studies were conducted in order to obtain the gradation graph and the water absorption of aggregates (Perlite, sand and gravel). In this study, gravel with specific gravity of 2.68 gr/cm^3, sand with specific gravity of 2.64 gr/cm^3 and Perlite with specific gravity of 0.15 gr/cm^3 were used as concrete aggregates. The cement used in these experiments was type I. In order to make the concrete, according to previous studies, the A3 type of Perlite with grain size 0.1 to 1 mm was used. The A1 and A2 types of Perlite are not suitable to be used in concrete due to very fine grain sizes. The A4 type with grain size 1 to 3 mm has very low grain resistance and is not used in concrete construction.

The gradation graph obtained from the primary experiments for sand and gravel are showed in Figures 1 and 2. The gravel, sand and Perlite water absorption were measured to be 1%, 1.5% and 63% respectively.

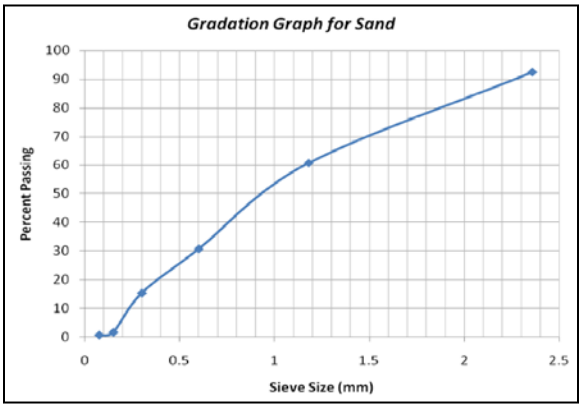


Figure 1. Gradation graph for sand.

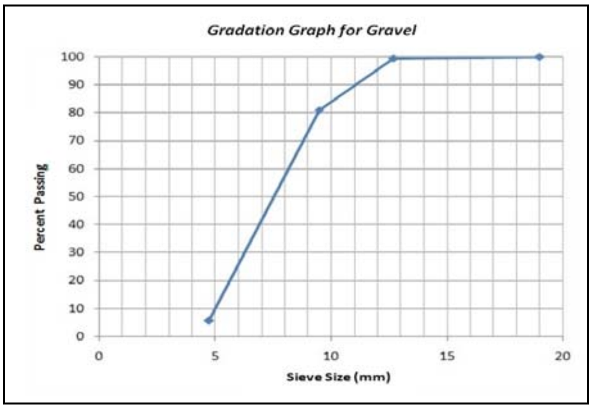


Figure 2. Gradation graph for gravel.

2.2. Concrete Mix Design

The mix design for making the desired Perlite concrete in this study is illustrated in Table 2.1.

Table 2.1. The mix design of Perlite concrete.

Perlite (kg/m^3)	Super Plasticizer/ Cement	Sand (kg/m^3)	Gravel (kg/m^3)	(Water/Cement)	Cement (kg/m^3)
213	0.015	709	851	0.35	320

2.3. Testing the Samples of the Perlite Concrete

For the intended Perlite concrete, the slump was measured to be 6.5 cm. The lack of enough slump can be explained in two ways: First, the Perlite concrete has a low density (about 2 gr/cm^3) and is considered to be a lightweight concrete, so when poured into the cone for slump test, it has less tendency to settle, due to its low gravity. Second, regarding the high ability of Perlite in absorbing the water, the mixture becomes dry and its workability is reduced.

In order to carry out the compressive strength test, 3 cubic specimens of the mentioned mix design of the Perlite concrete were made. The specifications of these specimens together with the values of their 28-day compressive strength, obtained from the tests, are shown in Table 2.2.

Table 2.2. The specifications of the cubic specimens and the result of compressive strength tests.

Specimen Number	Specimen Dimensions (cm^3)	Mass (gr)	Density (gr/cm^3)	28-Day Compressive Strength (MPa)	Actual Compressive Strength (MPa)
1	10×10×10.15	2080	2.05	20.3	16.24
2	10×10×10.1	2085	2.06	19.4	15.76
3	10×10.1×10.1	2100	2.06	19.7	15.52

The actual compressive strength of the concrete is approximately obtained by 80% of the 28-day compressive strength of small (10×10×10 cm^3) cubic specimens. The cubic specimens that were used in the compressive strength test are shown in Figure 2. This photo was taken after the test and the cracks on the surface of the concrete specimens can be seen in Figure 2.

Figure 2. Cubic Perlite concrete specimens after the compressive strength test.

In order to obtain the stress-strain diagram for the Perlite concrete, compressive strength test was carried out on 3 cylindrical specimens by Universal Testing Machine (UTM). The specifications of these specimens are shown in Table 2.3 and Figure 3.

Table 2.3. The specifications of cylindrical specimens.

Specimen Number	Specimen Dimensions (H×D) (cm^2)	Mass (gr)	Density (gr/cm^3)
1	20.5×10.1	3320	2.02
2	20.48×10.02	3280	2.03
3	20.65×10.2	3310	1.96

Figure 3. Cylindrical specimens.

The stress-strain diagrams obtained from these test for each specimen are illustrated in Figures 4, 5 and 6. The measured compressive strength for these cylindrical Perlite concrete specimens are shown in the following Table 2.4.

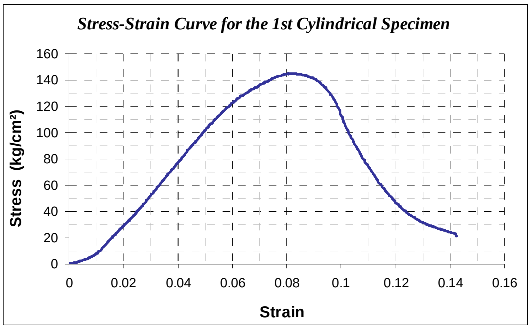


Figure 4. Stress-Strain curve for the 1st cylindrical specimen.

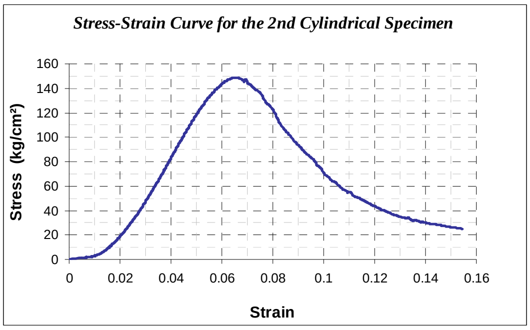


Figure 5. Stress-Strain curve for the 2nd cylindrical specimen.

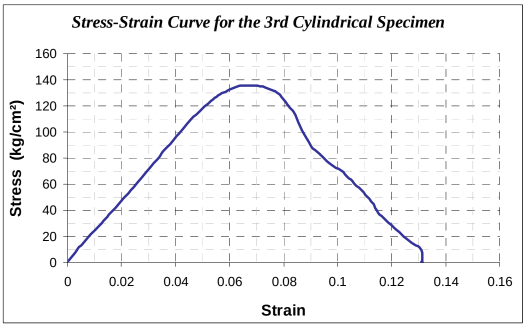


Figure 6. Stress-Strain curve for the 3rd cylindrical specimen.

Table 2.4. Test results of cylindrical Perlite specimens by UTM.

Specimen Number	Density (gr/cm^3)	28-Day Compressive Strength (MPa)	Failure Strain
1	2.02	14.52	0.083
2	2.03	14.87	0.065
3	1.96	13.74	0.066

As mentioned before, the purpose of making Perlite concrete in this study was to use it as filler in the tubes of the devised connection. According to the results of the tests carried out on the samples of the concrete, the Perlite concrete has a compressive strength of approximately 14.5 MPa while having a density of about 2 gr/cm^3, which is regarded to be desirable in comparison with the compressive strength of normal concrete being about 21 MPa with a density of 2.4 gr/cm^3. Furthermore, the considerable strain of the concrete subjected to loading which is observed in the stress-strain curves obtained from the experiments conducted by the UTM, is favourable to the purpose of this study.

3. THE DEVISED CONNECTION

The Khonsar^{TM} connection was invented in the 90s by the first author. This beam-to-column connection has two basic configurations. The HLT (Horizontally-Laid Tubes) configuration and VLT (Vertically-Laid Tubes) configuration of the connection are shown in Figures 7 and 8. If one vertical tube is placed between the two horizontally-laid tubes in the HLT configuration of this connection, will increase the shear strength of the connection, preventing the behaviour of the connection from entering into shear mode. The experiments conducted in this study to investigate the flexural behaviour of the innovative connection, are specifically carried out on this configuration of the connection. The detail of the specimens and its dimensions can be seen in Figure 9. The horizontal tubes were filled with Perlite concrete in order to increase the initial stiffness of the connection.

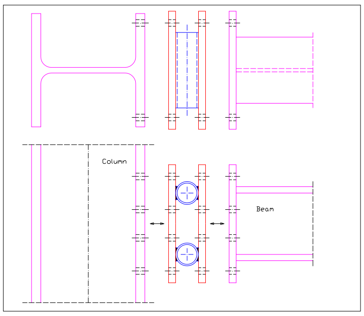


Figure 7. HLT configuration of the connection.

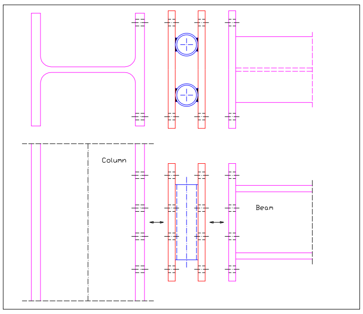
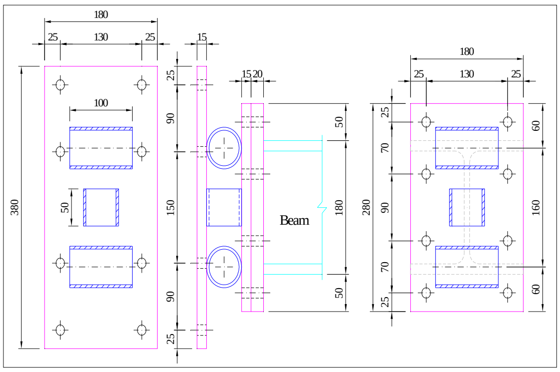


Figure 8. VLT configuration of the conenction.

The test assembly designed to enable the application of monotonic loading to the specimens of the connection through UTM is shown in Figure 10. This setting is consisted of three main parts: Column member (IPB 180 section), Beam members (IPB 180 section) and Restraints.



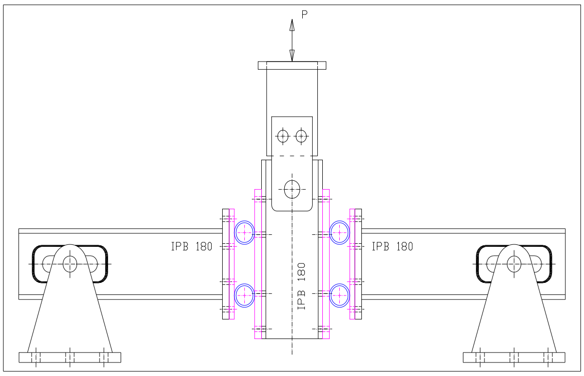


Figure 9. Detail of the specimens used in this study. The horizontal tubes are filled with Perlite concrete.

Figure 10. Test assembly.

3.1. The Experimental Studies on the Concrete-Filled Version of the Connection

The observations and results of the monotonic tests carried out on the specimens with concrete-filled tubes are provided in this part. Two types of specimens, according to the size of tubes used in the connection, were tested in this study. The first monotonic test was organized on specimens with 60 mm of diameter of tubes and is named HLT-CF-M1 (see Figures 11 & 12). The second monotonic test was conducted on specimens containing tubes with 72 mm of diameter and is called HLT-CF-M2 (see Figures 13 & 14). The result of the tests, including initial stiffness and yield strength of the connection, geometrical and material properties of the tubes used in the specimens of each test assembly, are given in Table 3.1.

Figure 11. HLT-CF-M1 before the test.

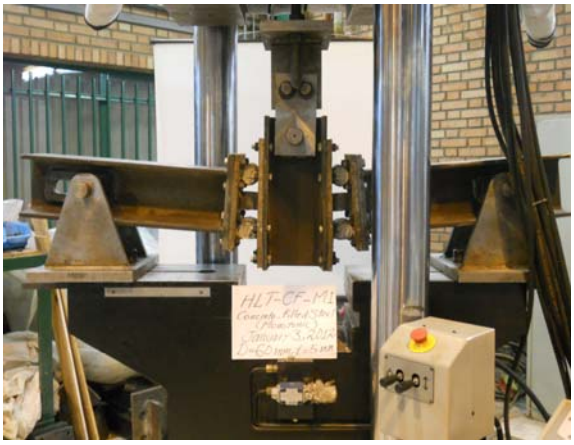


Figure 12. HLT-CF-M1 at the end of the test.

The first test was stopped before the failure of the connection due to deformation of the column member. Therefore in the second test, the column member was web reinforced with stiffener plates. Although in the second test the assembly withstood more monotonic bending load, the deformation started to occur in the column member again. The second test was also halted before the final failure of the connection.

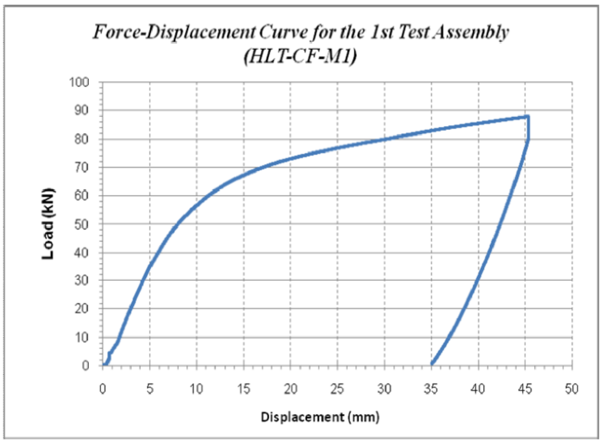
Figure 13. HLT-CF-M2 before the test.

Figure 14. HLT-CF-M2 at the end of the test.

Table 3.1. The properties of the specimens and the result of the tests.

Specimen's Properties	HLT-CF-M1	HLT-CF-M2
Outside Diameter of Tubes (mm)	60	72
Inside Diameter of Tubes (mm)	50	60
Thickness of Tubes (mm)	5	6
Length of Horizontal Tubes (mm)	100	100
Length of Vertical Tubes (mm)	50	50
Average Diameter to Thickness Ratio	11	11
Total Volume of Concrete in Tubes (cm^3)	392.7	565.48
Total Volume of Tubes (cm^3)	215.98	311.03
Initial Stiffness (kN/mm)	6.84	7.68
Unloading Stiffness (kN/mm)	8.52	8.94
Yield Displacement (mm)	6	7
Yield Strength (kN)	42	56
Ultimate Displacement (mm)	N/A	N/A
Ultimate Strength (kN)	N/A	N/A
Yield Moment (kg.m)	2250	2800
Yield Rotation (Radian)	0.016	0.02

The Force-Displacement and Moment-Rotation curves obtained from the experiments on concrete-filled version of the connection illustrate the increment of the initial stiffness in comparison with the previous experimental works on the bending behaviour of the connection with empty tubes. The following Figures 15 to 18 depict the result of the tests and improved flexural behaviour of the new connection.



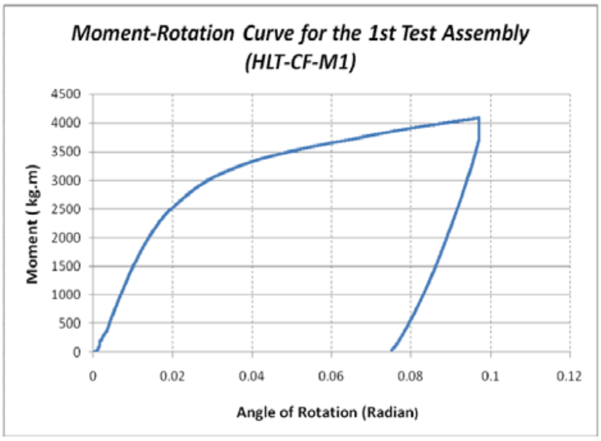
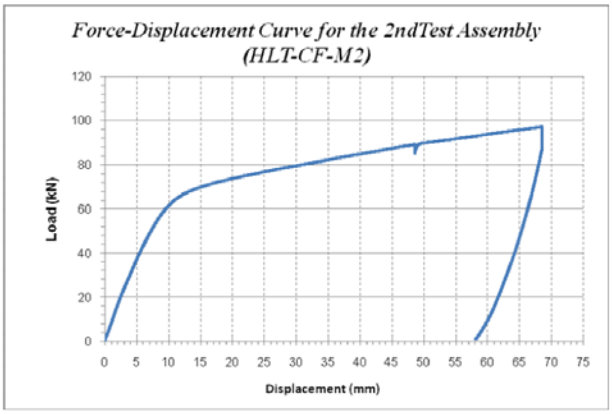


Figure 15. Force-Displacement curve for HLT-CF-M1.

Figure 16. Moment-Rotation curve for HLT-CF-M1.



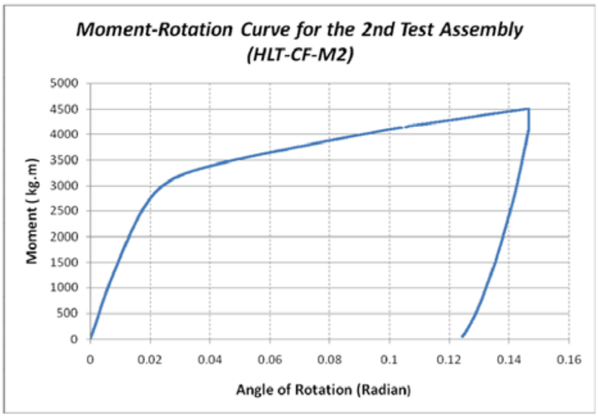


Figure 17. Force-Displacement curve for HLT-CF-M2.

Figure 18. Moment-Rotation curve for HLT-CF-M2.

As it can be observed, in the elastic region, the specimen with thicker tubes has higher values for stiffness and yield strength. However, the yield displacement and rotation in both types of specimens are approximately the same. As the load and displacement increases, the connection enters the plastic zone. In this area, the increasing trend of strength in the specimens with smaller tubes (D=60 mm) is noticed to be faster in comparison with the specimens containing bigger tubes (D=72 mm). Furthermore, in plastic region, the stiffness of the connection with thicker tubes, decreased more quickly. Thus, for large deformations, the connections with smaller tubes in spite of having less initial stiffness, proved to be more efficient due to their higher strength and stiffness.

The most important factor in evaluating the energy absorption of a connection is its ability to endure large deformations. The devised connection investigated in this study and also in previous experiments, has proved to have a great potential in energy dissipation.

4. CONCLUSIONS

The results of this study were compared with those of the previous experiments done in order to investigate the bending behaviour of the devised semi-rigid connection. The following conclusions can be drawn from the current investigation on the improved concrete-filled Khonsar™ connection.

1- Filling the tubes of this connection with a not-much-rigid material, such as Perlite concrete, proved to be successful in improving the initial stiffness of this connection.
2- The strength of the tested specimens was also improved as a result of concrete-filling.
3- Due to the nature of this connection for which the strength and stiffness are not dependent on the rotational capacity, the improvement in the strength and stiffness is not achieved at the

cost of any loss in the rotational capacity.

4- As a result of the achieved improvement in the strength and stiffness of the connection, its energy absorption capacity is much improved.
5- Due to the low cost of the added material and the lack of any need to any special expertise for its manufacturing, the addition of Perlite concrete to this connection does not involve a substantial increase in the cost of the connection.
6- Although choosing the Perlite concrete as a filler material with desired modulus of elasticity seemed satisfactory, it can be substituted with other substances, i.e. compacted high dense plastic. However, the cost of making the connection plays a great role in widespread manufacturing and should always be considered and optimized by choosing the best materials.

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