TTMJ – The New System For Slurry (Diaphragm) Wall Joints: from theory to practice

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ABSTRACT: TTMJ is the acronym for the Diaphragm Wall Tension Track Milled Joint currently in development as part of the European Union's innovative and far-reaching Horizon 2020 initiative (FTI Pilot-2015-1 720579). The TTMJ system is protected by various patents and is currently under development by a consortium comprising TREVI SpA (Italy), Arup (Netherlands) and CCMJ Systems (UK). The TTMJ System is a method of forming panel joints in diaphragm walls. The system can be theoretically used to any depth to provide a water tight joint, and a tension and shear connection between adjacent panels. The tension connection feature is of particular interest in seismic areas to create the continuity between diaphragm panels or even to replace capping beams. A number of full-scale tests have been carried out to date in order to validate the system features, including joint trimming, secondary panel concreting and tension joint split tests. This paper focuses particularly on the tension connection system, by describing the experimental full-scale split tests and comparing these against 3D non-linear back analyses. The combination of experimental and numerical tests is aimed to provide a solid framework to the design of tension joints in real projects by means of the TTMJ method.

Keywords: Slurry Walls, Diaphragm Wall, Joints, CWS, Seismic, Basement.

1 INTRODUCTION

The average depth of Diaphragm Walls has increased steadily over the last 50 years or so. When the technique was first developed in the 1950s, the grabs had rounded clamshells and the joints were formed by installing steel tubes at the end of the panel and extracting them immediately after the concrete had achieved an initial set.

In the second half of the 1980s the “peel off” Coffrage avec Water Stop, or Complete Water-Stop (CWS) steel joint former came into use, particularly in Europe. This became a highly successful and efficient method for forming the joint between adjacent slurry wall panels. The joint could also incorporate a water stop. However, as slurry wall depths have increased, problems have arisen with the removal of the CWS joint formers. It was found that beyond 30m it was sometimes difficult and time consuming to peel them away from the concrete of the previously constructed panel.

Installing a tension connection between individual diaphragm wall panels is carried out in some countries (mainly in eastern Asia) but the methodology, which comprises the use of fabric bags around the reinforcement cage and gravel poured behind the permanent steel joint former, has not been adopted in Europe and North America.

The TTMJ System (Crawley et al. 2017, Crawley et al, 2018) utilises tracks cast into the ends of a diaphragm wall panel to guide a machine (the TTMJ Trimmer) to trim back the concrete at the end(s) of the panel, to form a construction joint to any depth. A shear key and water-stop can be provided, and the system can allow for some tension connection between adjacent panels if required.

2 TTMJ COMPONENTS

The TTMJ track is installed with the reinforcement cage. A typical before and after arrangement is shown in Figure 1.

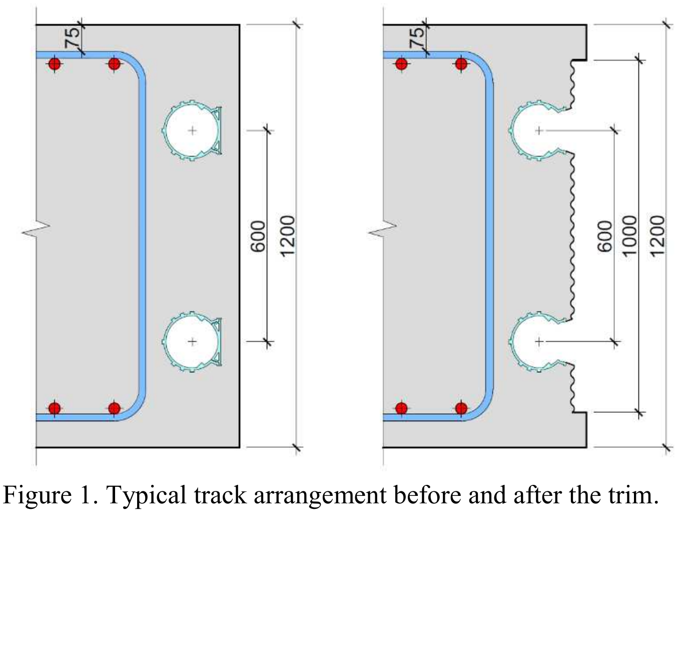

Figure 1. Typical track arrangement before and after the trim.

Figure 2. Samples of the track.


Figure 3. TTMJ trimmer in action.

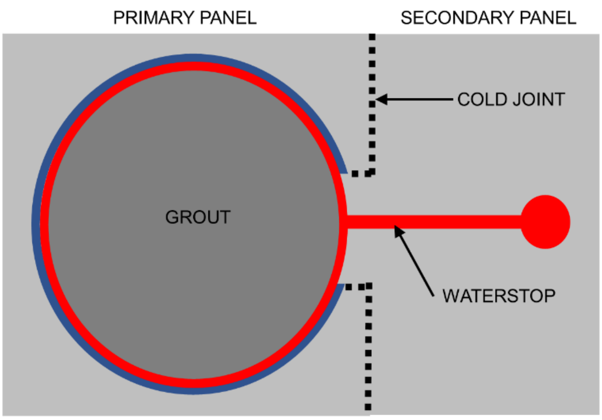

Figure 4. Sketch of sleeve/waterstop installation.

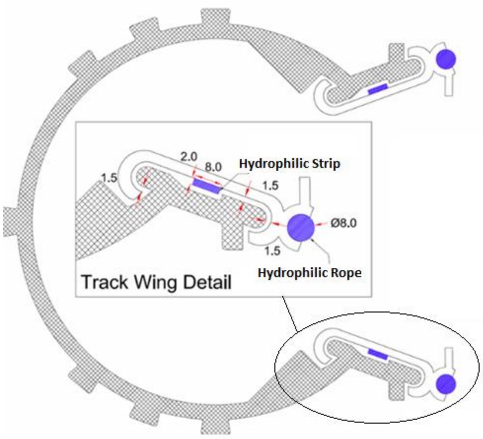

Figure 5. Modified TTMJ track with hydrophilic cords.

The track is manufactured from pultruded GFRP and is approximately 150mm in diameter. The track has external shear strips to anchor it into the concrete as well as a sacrificial arc to be removed by the trimmer as it prepares the joint (Figure 2). The TTMJ trimmer, used for milling the joints, is shown in Figure 3.

The TTMJ System allows the installation of a water bar across the panel joint. Figures 4 and 5 show two alternative water stop systems compatible with the System. In Figure 4 a combined sleeve/waterstop is installed into the track after the trimming phase. The sleeve is then grouted.

In Figure 5 the wings of a modified TTMJ track are used to guide and retain a PVC extrusion into which a continuous hydrophilic cord is clipped. To provide a tension connection across the joint "T" headed reinforcement bars can be used as shown in Figure 6.

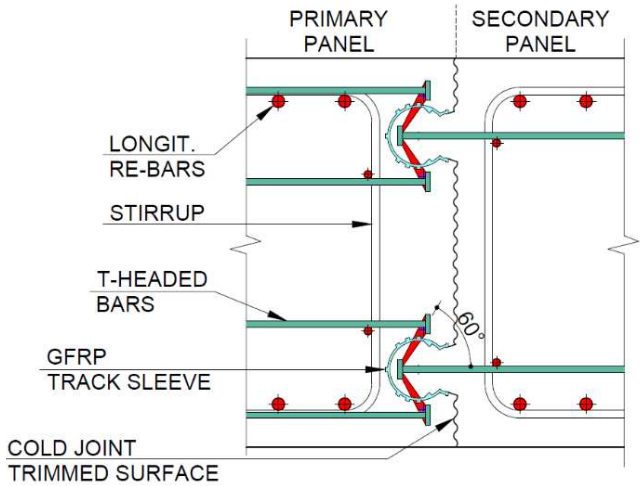

Figure 6. Tension connection with T headed bars across joint.

3 PRELIMINARY TESTS

The selection of the TTMJ track material and physical properties was an "educated guess". Before field trials could be contemplated it was essential that the actual restraint likely to be provided by the track was established. It was also important to determine the maximum force required to remove the sacrificial PVC arc. Additionally, the intended arrangement of the tension connection needed to be verified and the potential tension capacity evaluated. During the latter half of 2017, over 50 blocks of concrete were cast, with various track and reinforcement arrangements, and tested to failure. The blocks ranged in size from 400 mm x 500 mm x 300 mm deep to 800 mm x 500 mm x 450mm deep. For the track pull out tests the samples were tested when the concrete had a compressive strength of approximately 20 MPa and for the tension tests when the concrete had a compressive strength of approximately 40 MPa. Figure 7 shows one of the tension (split) test blocks in the test rig and Figure 8 the block after testing.

Figure 7. Preliminary Tension test to estimate the resistance of one bar.

Figure 8. Test Block after testing.

4 FIELD TRIALS

The field trials of the TTMJ System took place in March 2019 at TREVI's sister company SOILMEC's factory in Cesena (Italy). Within the facility, SOILMEC has a steel lined shaft 1.5 m wide, 3.0 m long and 20 m deep, which was used for the field trials which consisted of the following phases:

– trimming of three 20m long beams;
– concrete pouring trial;
– extraction of the cast in situ concrete block for visual inspection and slicing into sections for the split tests.

By means of a system composed of sacrificial concrete elements connected to a steel beam and a reaction frame, three trimming trials were carried out in the first phase of the trials; one on a concrete test beam with a flat face, one on a beam with an inclined face representative of forming the joint for a circular shaft and one on a beam with a bulging face representing the occurrence of concrete overbreak. Figure 9 shows the test beams prior to installation, while Figures 10 and 11 show the concrete surface and embedded TTMJ tracks after trimming.

Figure 9. Test beams prior to installation into the shaft.

Figure 10. Bottom section of the beam with the inclined face showing the concrete profile before and after trimming.

Figure 11. Concrete surface and embedded TTMJ tracks after trimming.

One of the trimmed beams was selected for the concrete pouring trial. Figure 12 shows the 10 m long steel mould which was attached to the lower half of the chosen beam (left), and the fibre optic cables used for monitoring the quality of the concrete (right).

Figure 12. Mould (left) and cage installation (right).

The pouring trial was carried out using a standard “contractor’s method” with a 340mm diameter tremie pipe and concrete class C35/45.

After 10 days’ curing, the trimmed beam and attached cast in situ block, with a total weight of about 70 tons, was lifted out of the shaft, placed on the ground and the mould removed (Figure 13). The combined beam and block was then sawn into three 2.5m long sections and the upper and the lower parts discarded (Figure 14). This allowed the quality of the cold joint between the beam and the cast in situ panel to be checked and in particular the quality of the concrete inside the tracks to be visually inspected.

5 SPLIT TESTS

5.1 *Preliminary numerical analyses*

A preliminary finite element model was created in LS-DYNA (LS-DYNA Manual R11.0, 2019) by Arup in order to carry out a blind prediction of the joint behaviour when subjected to tension forces. This preliminary model was based on as built drawings and on expected mechanical properties of concrete and steel (Figure 15).

The model was created with a mesh size fine enough to capture cracking and non-linear behavior with accuracy. More in detail, the mesh size of the solid elements in the cross-section plane is about 1.5x1.5cm or smaller. With the purpose of limiting the computational time required for the analysis to run, assuming nearly uniform conditions along the 2.5m sawn beam, a model length of 0.5m was deemed appropriate. Concrete is modelled with a smeared crack model, implemented for the 8-node single integration point solid elements, based on the Ottosen plasticity model (*MAT_WINFRITH_CONCRETE). The model was implemented by Broadhouse and Neilson in 1987 and has been validated against experiments.

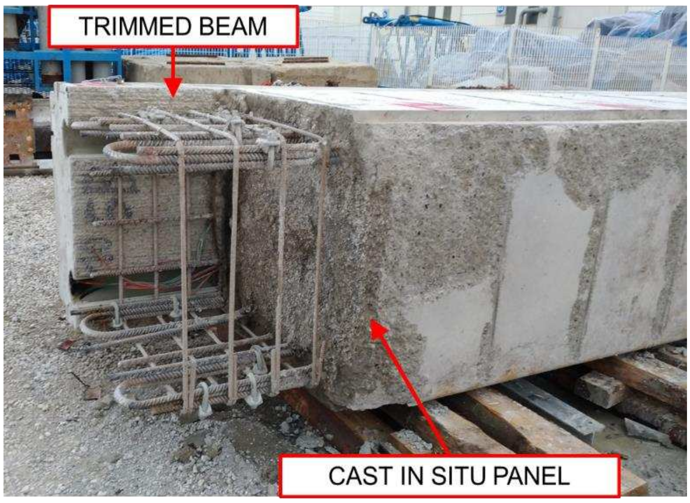

Figure 13. Cast in situ element after extraction.

Figure 14. Sawn face of the combined beam and block showing the concrete infilled TTMJ tracks.

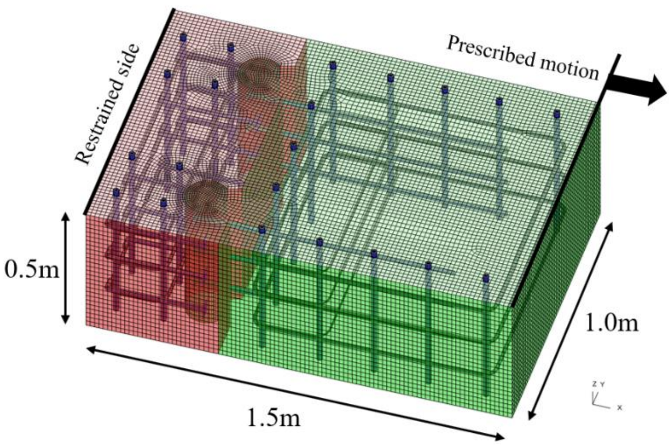

Figure 15. Finite element model (tension test).

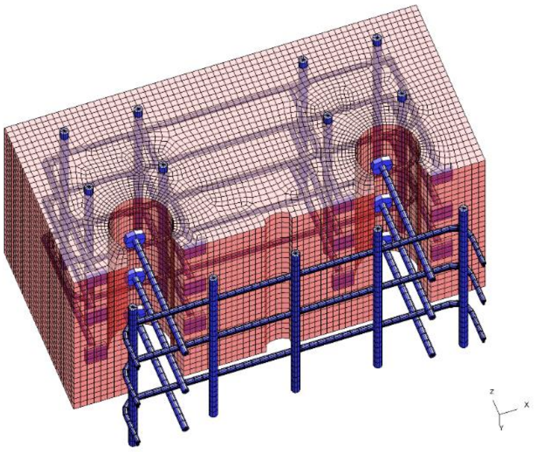

Figure 16 Finite element model: detail of rebars arrangement.

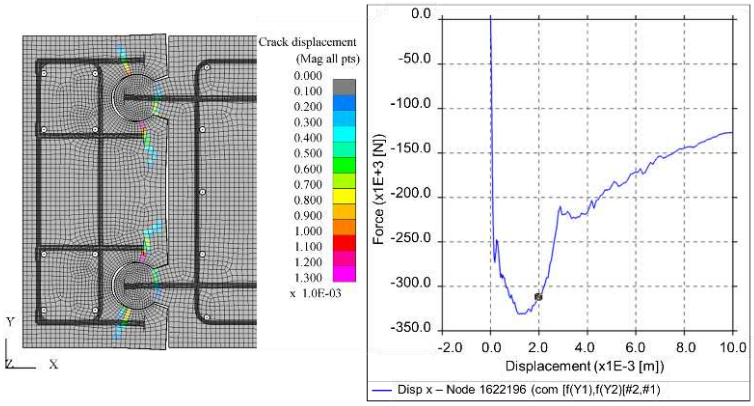

Figure 17. Model blind prediction results.
Force [N] – crack displacements [m].

Concrete mechanical properties are based on concrete grade C35/45. As shown in Figure 16, steel bars are modelled with beam elements and steel reinforcement heads are modelled with shell elements with a material that is able to capture isotropic and kinematic hardening plasticity of steel elements (*MAT_PLASTIC_KINEMATIC). Steel mechanical properties are based on steel grade B450C and the reinforcement layout is correspondent to the reinforcement cast into the laboratory specimen. Bonding between concrete and reinforcement has also been modelled (*CONSTRAINED_LAGRANGE_IN_SOLID) to simulate the interaction between the materials even if the mesh nodes of concrete and steel beams do not match. A perfect coupling was considered for both tension and compression. The contact between primary and secondary panels is modelled with an *AUTOMATIC_SURFACE_TO_SURFACE contact. No initial penetration between the nodes of the two different blocks are present at the beginning of the analysis. The contact is a compression only contact that also implements the friction between the blocks. In particular, the concrete-rubber friction coefficient is used in the simulation.

The preliminary analysis was carried out considering the system horizontally supported on its cross section. One side of the combined structure was fully restrained, and a prescribed motion was applied on the other side. The results of the preliminary analysis (cracking pattern and force-displacement curve) are shown in Figure 17.

The preliminary results showed a stiff initial behavior with an elastic branch till the first crack opening at about 0.1-0.2mm displacement. The peak force was registered for a 1mm displacement with a value equal to 330kN and a clear descending branch is visible after the peak force occurred. Considering the length of the model (0.5m), a value of 660kN/m was assumed as the force required to bring the structure to failure.

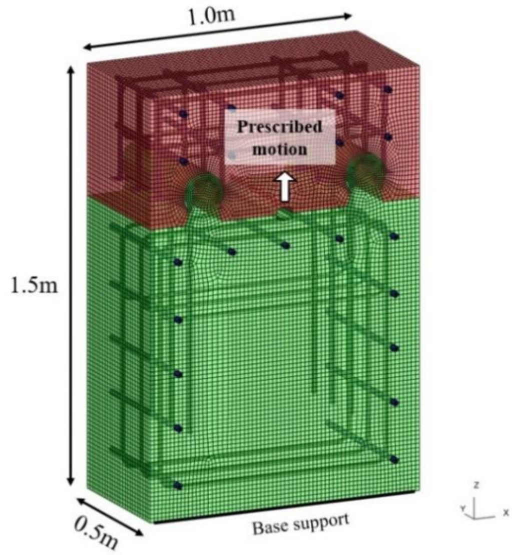

Figure 18. Final finite element model used to back analyse the tests (split test).

Since in experimental tests tension is induced by a rock splitting device (see Section 5.2), the mesh was adapted to allow for a circular hole at the interface between primary and secondary panel by removing some of the solid elements (Figure 18).

A prescribed motion was applied to the top surface of the hole in a positive vertical direction. The comparison between the results of such model with the previous one (Figure 17) in terms of force-displacement curve and in terms of cracking pattern confirmed the appropriateness of using the rock splitter to simulate tension d-wall behavior during experimental tests.

The above-mentioned results were therefore used to plan laboratory test layout, selecting rock splitting devices and to better define the positions of the strain gauges.

5.2 *Test set up*

Three real scale split tests of the TTMJ System were executed in May 2019 at TREVI's premises in Cesena Italy.

Three elements of the wall portion including the joint between the panel and the test beam were sawn out and set in horizontal position on top of a specific support system to serve as samples for the test. Each sample was 1.0 m wide, 2.5 m long and 1.48 m high with some differences only on the stirrups restraining the concrete volume around the tracks.

Each sample was drilled through in order to create a longitudinal hole for the entire length with the scope of accommodating two special hydraulic jacks per hole (Figures 19 and 20) able to "split" the panel portion from the jointed beam portion.

The relative displacements between the two portions during the splitting test were measured by means of 16 potentiometric displacement transducers, model PY2, straddling the strip where the surface fractures were, according to the numerical analyses, going to occur. Four transducers were applied to each side of the sample with a maximum stroke of 10 mm (Figure 21).

An optical measurement system was also used as it was capable of following the absolute displacement of several fixed points (targets) on the front face of the sample. The resolution obtained by this system is calculated by dividing the size of the framed field by the number of pixels, leading in this case to a value around 0.02 mm. The image analysis software was able to provide, during testing, the real-time displacement vector for every target.

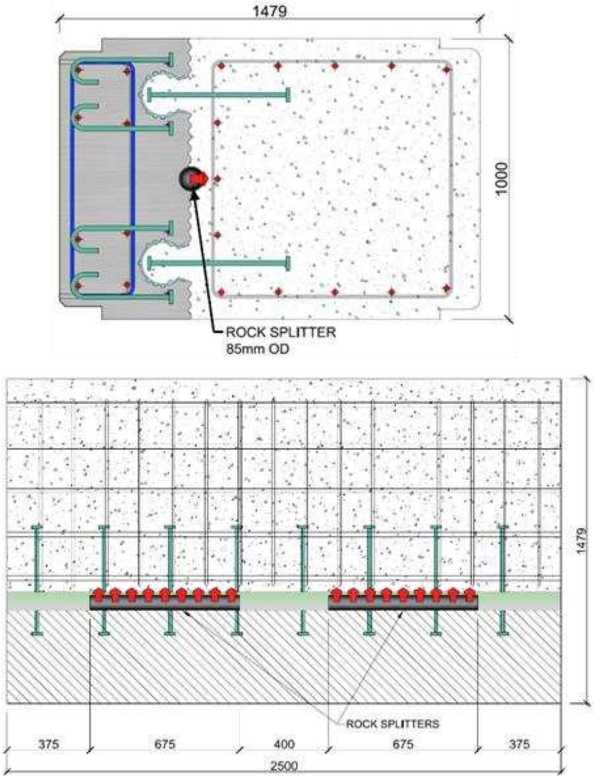

Figure 19. Split test sample: cross and longitudinal sections .

Figure 20. Rock splitters.

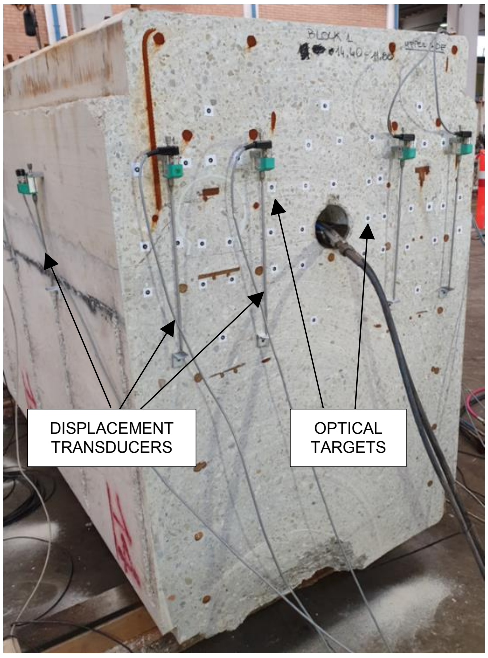

Figure 21. Test layout with optical targets and displacement transducers.

5.3 *Test set up*

After the completion of the experimental split tests, the LS-DYNA analytical model was adjusted to minimize the differences in terms of boundary conditions and prescribed loads with respect to the real test. In particular, blocks were placed in vertical position and the base nodes of the bigger block were restrained.

It can be noted that the crack pattern observed at the end of the laboratory test appeared to differ slightly depending on the specific layout of the test and the point of application of the rock splitters. However, the final crack patterns of the blocks are very similar to the crack pattern observed at the end of the numerical simulation in LS-DYNA.

Cracking pattern and force-displacement curves are shown in Figure 22 and 23 and they are compared with the laboratory test results (Figure 24).

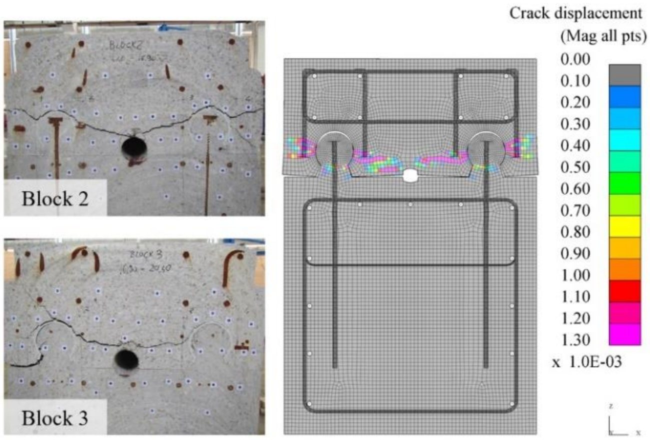

Figure 22. Comparison between experimental and numerical results.

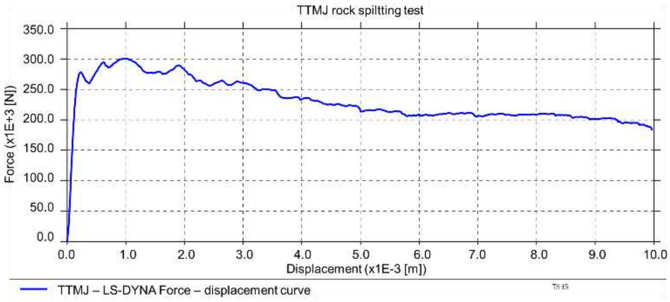

Figure 23. Force-displacement curve (numerical analysis).

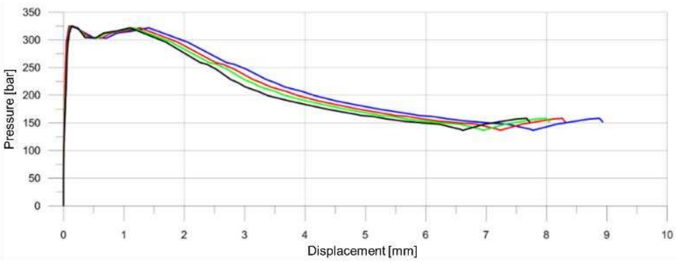

Figure 24. Pressure-displacement curve (experimental results).

The force peak observed in LS-DYNA is about 300kN and the sample length is 0.5m, leading to a value of about 600kN/m of resisting force. In addition, the trend of the curve observed in the LS-DYNA numerical simulation follows very closely the trend of the laboratory test output curve, with very similar linear and descending branches.

The pressure at first peak failure observed during the laboratory test ranges between 300 to 375 bar for the three tested samples. The tests were carried out using two rock splitters type PC-80, with a total of 22 pistons. Each piston has a diameter equal to 45mm. The total force can be derived as follows

$$F = pressure \cdot n_{pist} \cdot A_{pist} \tag{1}$$

The force ranges between 1050kN (300bar) to 1312kN (375bar). The length of the specimen is equal to 2.5m. Assuming that the specimen resists the rock splitter pressure for the 90% of its length (a smaller value is considered due to the cuts and the edge effects), the force per unit length can be obtained from the values above.

$$F_{min} = {}^{1050}/_{(0.9 \cdot 2.5)} = 466\ kN/m \tag{2}$$

$$F_{max} = {}^{1312}/_{(0.9 \cdot 2.5)} = 583\ kN/m \tag{3}$$

This force ranges between 466kN/m and 583kN/m. The value of the LS-DYNA analysis (about 600kN/m) seems to be a bit larger compared to the laboratory tests.

The difference in length of the LS-DYNA model and the specific laboratory test layout (with two rock splitters, not captured by the analysis), can be considered as the main reasons to explain the difference in the comparison.

6 CONCLUSIONS

The field trials were very successful and the TTMJ System is now ready to be applied on a real project.

The split tests results are encouraging as some traction forces can be absorbed by the joints connection, even if some further optimisations will be probably necessary in order to maximise the capacity of the tension connection. The successful use of advanced numerical analyses to capture the behaviour of such complex tension joint will enable the estimation of such capacity at design stage in the presence of different geometry, concrete grade and steel arrangements. Moreover, the concrete surface finishing produced by the trimmer resulted quite "rough", leading therefore to an increment of the vertical shear plane resistance along the panel joints with respect to what is currently achievable when steel joint formers are used. Such benefits in terms of flexural and shear resistance at the panel joints indicate that the use of TTMJ system for the construction of underground structures could also result in an improved structural performance in seismic conditions. Some further trial tests are planned to further explore this assertion.

7 ACKNOWLEDGEMENTS

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