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EXPERIMENTAL AND ANALYTICAL PERFORMANCE OF AN INNOVATIVE PILE-TO-PILE MECHANICAL CONNECTOR

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Abstract: Pile-to-pile mechanical connections are used if the depth of the soil layers with sufficient bearing strength exceeds the original (“leading”) pile length. The additional pile segment is termed “extension” pile. Mechanical connectors consist of an assembly of sleeve-type external couplers, pins, and other mechanical interlock devices that ensure the transmission of forces between leading and extension pile segments. However, the followed common practices when designing mechanical connectors neglect important aspects of the assembly response, such as stress concentration around pin holes, torsional stresses from the installation process, and interaction between the forces at the installation and service stages. This translates into potentially unsatisfactory designs in terms of the ultimate and service limit states, exhibiting either reduced strength or excessive deformations. In this study, the experimental response under compressive forces of a type of mechanical connector is presented, in terms of strength, deformation and failure modes. Using the results from the compressive tests, an analysis model is developed using the Finite Element (FE) method to study the interaction of forces under installation and service stages of a typical mechanical connector. The response of the analysis model is used to identify potential areas for design optimization, including size, gap between leading and extension piles, number of pin/bolts, hole sizes, and material properties. The results show that the design of mechanical connectors should consider the interaction of forces present at every stage of their life cycle, and points out the most critical zones of the mechanical connection.

1 INTRODUCTION

A mechanical connection in helical piles is a solution to reach soils deeper than the length of a standard pile. The system allows the assemblage of two piles using steel bolts and an external coupler. All the components in the mechanical connection are analyzed using the FE Analysis software ABAQUS.

The current study is focused in presenting the validation of a FE model of a tested specimen of a mechanical connection under an axial compressive load. The results of the test are retrieved in the form of load-displacement relationship. The most vulnerable areas of the connection are visually identified in order to find the best optimization opportunities of the assembly.

Once the test is conducted and the results retrieved, a FE model is developed in ABAQUS by creating an exact replica of the specimen tested in the laboratory. This model provided the great advantage of presenting the results not only in terms of loads and displacements, but also the distribution of stresses and the location of the highest stress throughout the whole surfaces of the assembly.

A comparison between the tested assembly and the FE model is conducted to validate the latest. Once the model is validated, a myriad of changes can be done to the model to identify the most suitable design of the mechanical connector without compromising, neither the integrity nor the capacity of the complete system.

2 PROPERTIES OF THE MECHANICAL CONNECTION

2.1 Geometry of the model

The complete system is composed (from top to bottom) by the extension pile, the fillet weld, the external coupler, three steel pins and the lead pile. The extension pile and the external coupler are welded by a fillet weld and four points of plug welds. The external coupler and the lead pile are assembled together by the steel pins. Figure 1 shows the components of the assembly as it is tested in the laboratory.

The two internal piles have an outer diameter of 273.05 mm (10.75 inches), and the external coupler has an outer diameter of 304.80 mm (12 inches). Table 1 summarizes the dimensions of all the components involved in the mechanical connection.

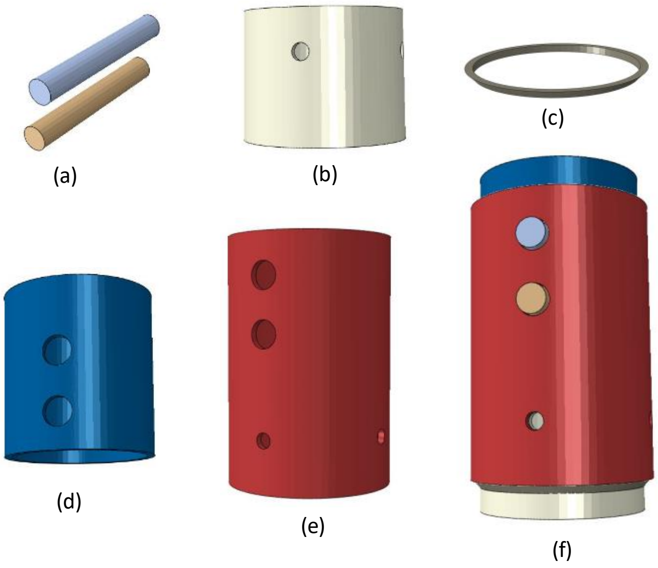


Figure 1: (a) Steel pins, (b) extension pile, (c) weld, (d) lead pile, (e) external coupler, (f) complete assembly.

Table 1: Dimensions in millimeters of elements in mechanical connection.

Properties	Coupler	Lead pile	Extension pile	Pins	Weld
External diameter	304.80	273.05	273.05	-	-
Internal diameter	279.40	247.65	247.65	-	-
Thickness	12.70	12.70	12.70	-	-
Length	457.20	279.40	228.60	330.20	-
Number of holes/pins	4	4	-	2	-
Diameter of holes/pins	50.8	50.8	-	47.625	-
Weld	-	-	-	-	1/2" fillet weld Plug welds

According to the provided dimensions, three gaps are being considered. One gap of 1.588 mm (⅛") is located at both sides between the pins and the holes of the piles. The second gap is 2 mm long and it is located at each side between the external coupler and both (lead and extension) piles. Finally, the third gap is the one existing between the lead and the extension pile. This gap has a length of 50.8 mm (2") and it is defined to determine the maximum deformation that will be allowed to the system. Once the two piles enter in contact, the loading capacity of the system is increased, and the analyses are stopped. This is done to rely only on the capacity of the mechanical coupler and the pins, and not on the interaction between the two piles. See Figure 2 for the details of the gaps.

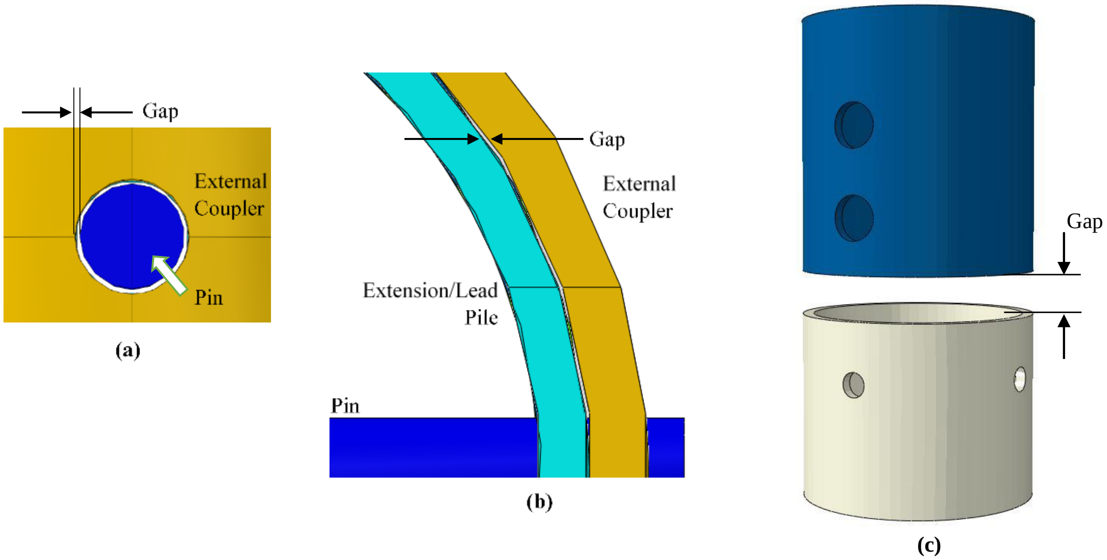


Figure 2: (a) Gap between pins and holes, (b) gap between piles and external coupler, (c) gap between piles.

2.2 Material Properties

The material properties of the components are provided by the manufacturer of the piles. Tensile tests are conducted on steel coupons obtained from the material used to produce the piles. The corresponding yielding and ultimate strength are defined for each component as follows:

Table 2: Yielding (F_y) and Ultimate (F_u) Strengths of the Material Used in Components of Mechanical Connection

Component	Steel Grade	F_y (MPa)	F_u (MPa)
Lead Pile	ASTM A252, Grade 3	400	600
Extension Pile	ASTM A252, Grade 3	400	600
Coupler	ASTM A252, Grade 3	400	600
Pins	ASTM A193, Grade B7/ AISI Grade 4140 HR HT	979	1069

As seen in table 2, the capacity of the pins is considerably higher than the capacity of the piles and the external coupler. This makes sense when is considered that the pins will be subject all the time to shear forces due to the application of the load to the walls of the piles in different directions. A brittle failure of the system should be avoided by providing enough resistance to the pins and allow instead large deformations in the zones near the holes of the piles.

3 EXPERIMENTAL WORK

Three specimens are fabricated to conduct the axial compressive loading test. Visual check and measurements are done to ensure that the three specimens fulfill the requirements of geometry, and that they are identical amongst them. Figure 3 shows one of the mentioned specimens in position before the beginning of the test.

Figure 3: Specimen of mechanical connection before test.

The three specimens are tested using an MTS 6000, which is a universal testing machine with axial compressive capacity up to 6000 kN. They are directly placed in position between the plates of the testing machine to be tested. There is no instrumentation placed in the specimens, nor any kind of frame. The compressive load is applied directly to the assemblies. The results retrieved are based on the displacement of the head of the machine and the reaction force read by the load cell included within the head of the machine. It can be noted that the specimens are placed in an inverted position compared to the position used on field, i.e. the lead pile is on top, while the welded extension pile and coupler are below. This is done to facilitate the process of capturing pictures through the test.

3.1 Specimen 1

As per AISI standard S905 a strain rate of 3 mm/minute or 2 kN/minute is indicated to perform compressive testing in steel structures (AISI 2008). However, it is considered that the ideal initial strain rate for the mechanical connection is 1 mm/minute. The load is applied until a displacement of 26 mm is recorded. This deformation is considered to be large enough for serviceability purposes in real conditions.

3.2 Specimen 2

The second specimen of the mechanical connection is subject to the same strain rate of 1 mm/minute. However, it is seen that this rate is slow and the deformations of the complete assembly could sustain an increased strain rate. Therefore, when the displacement reached 25 mm, as recorded from first specimen under 1 mm/minute rate, the strain rate is increased to 3 mm/minute. The load in this second specimen is applied until the extension and lead piles established contact, i.e. when the gap of 50.8 mm (2 inches) is closed.

3.3 Specimen 3

The third specimen is subject to the same loading conditions and strain rates as the ones used in the specimen No. 2. The load is applied until the gap between the extension and lead pile is closed. The results for all three specimens and the observations after the application of the load are explained with detail in the Results section of this paper.

4 FE MODEL

The geometrical and material properties of the specimens tested are defined in ABAQUS. All the components of the mechanical connections are modeled as 3D deformable solid bodies modeled by extrusion from a plan view. The holes in the piles and in the external coupler are defined by cuts from datum planes previously defined. Once all the components are modeled and added to the assembly, they are positioned with no initial interaction, i.e. no surfaces are in contact at the beginning of the analysis.

4.1 Mesh

The mesh in this model consists in elements type 8-node linear brick, reduced integration, hourglass control. This type of elements reduces the computation time without compromising the accuracy in the results (Dassault 2012). In the experimental tests conducted for the current study, it was found that the most critical areas of the mechanical connection are the holes in the external coupler and the lead pile. When the size of the mesh is reduced, the accuracy of the results will increase. This is the reason why a seed size of 12 is assigned for the piles and external coupler over the whole internal and external surfaces. But it is reduced to 5 in the diameter of the holes to have a more accurate set of outputs in these critical zones. The seed size used in the fillet weld is 12. A size of 7 was assigned to the elements in the pins. Figure 4 shows the finer mesh around the holes compared to the rest of the components.

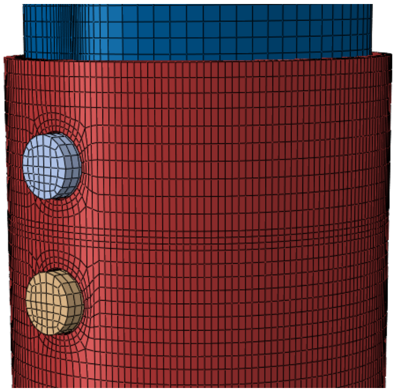


Figure 4: Increased density of mesh elements around the holes.

4.2 Fillet and Plug Welds

The assemblage of the lead pile and the external coupler is established through the steel pins. Whereas the extension pile and the external coupler must be welded before being assembled to the lead pile.

A ½” fillet weld is the welding procedure followed to achieve this junction of the pile and the coupler. However, four size plug welds are added as in the tested specimens.

When modeling the fillet weld, two tie constraints are implemented in the six degrees of freedom of the surfaces. The first of these constraints is between the coupler and the weld. The second one is established between the weld and the coupler. By assigning these constraints, the slave surfaces (pile and the coupler) will reproduce exactly what the master surface (weld) will do. This helps to avoid any kind of slippage between the weld and the piles. These constraints correspond to the assumption that the weld and base metal interaction will not fail during the application of the load.

When defining the properties for the plug welds, the same procedure as for the fillet weld is followed. Four holes are modeled in the extension pile and four more in the external coupler. These holes are perfectly aligned and then tied together using the tie constraint. The four holes will deform in the same amount and they will transmit the load from the extension pile to the external coupler alongside the fillet weld.

4.3 Steps

Two different steps are used to run the model. The first step is defined as Contact and it is created to conduct the displacement of the corresponding points (see Loading and Boundary Conditions later in this paper) until the engagement of the pins with the holes of the external coupler and the lead pile. Once this engagement is achieved, the second step, defined as Displacement, is initiated. This second step will take the displacement of the assigned nodes until the closure of the gap between the extension and the lead pile (see Geometry of the Model). The option Nlgeom is activated for both steps to account for geometric nonlinearity of the model.

4.4 Contact and interaction Properties

The contact interaction is defined as General Contact for the complete model. By doing this, it is not necessary to define the surfaces that could be in contact at any time of the analysis. This is done to avoid overlapping of the components in the assembly if any of the surfaces is neglected at the moment of defining the surfaces being in contact.

However, specific master-slave assignments are defined within the General Contact, as Contact Formulation. The surfaces of the holes in the external coupler and in the lead pile are defined as slave surfaces, since they are less stiff and they have a finer mesh. Whereas the pins, which are stiffer and contain a coarser mesh, are defined as the master surfaces. The Interaction Property defined for the General Contact is defined as Friction. Within this property, Normal and Tangential behaviors are defined. The Normal behavior property is defined as Hard contact for pressure-overclosure and the Default option provided by ABAQUS is left as the penalty method. The Tangential behavior property is defined by an Isotropic friction formulation penalty with a friction coefficient of 0.8 (AutoDrill, n.d.), commonly used for surfaces of steel in contact.

4.5 Constraints

Five Reference Points (RP) are assigned to different surfaces defined in the assembly. Three of them are independently coupled to the bottom surface of the lead pile, the top surface of the extension pile, and the central axis of the pins. The displacement and reaction force are retrieved from the first two RP. The constraints of displacement are applied to the third RP. The two remaining RP are assigned to the bottom surface of the extension pile and the top surface of the lead pile to avoid instabilities in the assembly. Figure 5 shows the location of all the mentioned RP.

4.6 Loading and Boundary Conditions

The axial compressive load is applied in terms of displacements. Since a static equilibrium must be kept, no dynamic properties are defined. Boundary conditions are assigned to all five RP created previously, and they will be defined as per the step in which they are applied.

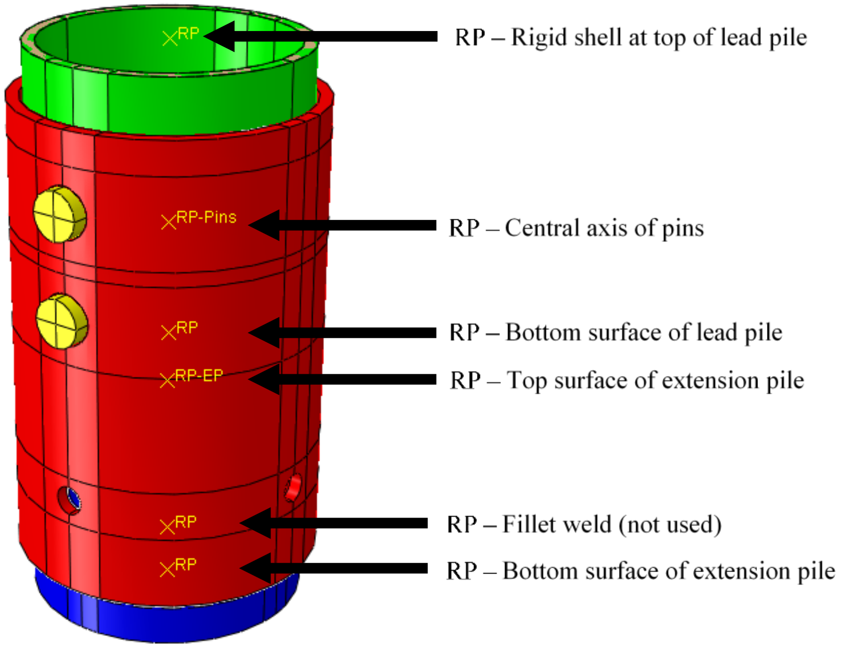


Figure 5: Location of reference points in the assembly.

4.6.1 Step 1: Contact

This step includes the displacement of the lead pile until the engagement with the pins. This displacement is applied to the RP coupled with the top surface of the lead pile, and it has a negative magnitude of 3.3 mm, which exceeds the complete gap between the pins and the holes. The remaining degrees of freedom of this RP remain fixed to represent a perfect vertical displacement. When the lead pile is being displaced downwards, the RP of the bottom face of the extension pile remains fixed in all its six degrees of freedom. Now a fixed-fixed system is being subject to a small a vertical displacement at the top. The remaining RP are assigned fixed boundary conditions in five degrees of freedom, whereas they are free to undergo into displacements in the vertical directions.

4.6.2 Step 2: Displacement

This step takes the displacement of the lead pile all the way until the closure of the gap between this pile and the extension pile. The boundary conditions of the RP of the top face of the lead pile are changed from a vertical displacement of 3.3 mm to a displacement of 50.8 mm. No other changes are made to this feature. The boundary conditions of the other four RP remain unaltered for this step.

5 RESULTS

5.1 Experimental Work

The results of the tested mechanical connections are very similar for the three specimens tested. The load-displacement relationship obtained from them is plotted in figure 6. It can be observed that specimen 1 was subject to a shorter test. However, out-of-plane deformations of the areas in contact with the pins are observed. The holes in the lead pile and in the external coupler are the first zones to deform and lead to the displacement of the complete assembly. There are no cracks observed in any of the components of the connection. The pins remained straight and with no deformations during the whole application of the load. A maximum load of 2700 kN is attained when the displacement of 26 mm is reached.

For the second specimen, the load is applied until the closure of the gap between the lead pile and the extension pile. It is seen in figure 6 that the maximum load attained is 3200 kN when the displacement reached 50.8 mm. Right before the two piles established contact, a drop in the load can be seen. This occurs when the overall displacement of the system is about 45 mm. After this drop in the capacity of the connection, the piles established contact and a sudden increment in the load capacity is observed. This sudden increment is neglected because the purpose of this investigation is to analyze the capacity provided only by the interaction between the pins and the holes in the piles. After removing the load and visual inspection is conducted, a crack pattern was found that could be interpreted as a block shear type failure in the zones between the two pins. Now it could be explained that the reduction in the load capacity of the system occurred when this crack appeared.

The third specimen presented a load-displacement relationship and failure patterns very similar to those in specimen 2. The same block shear between the two pins and the increment in the load after the two piles established contact are observed.

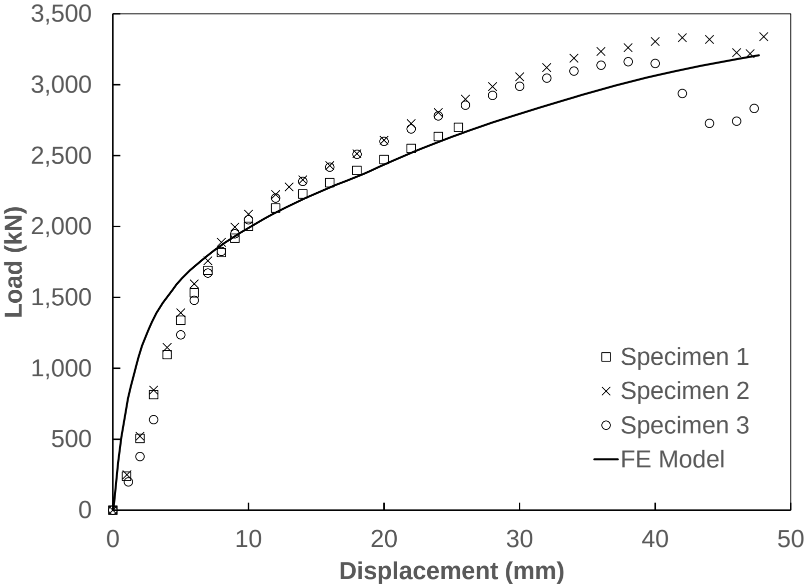


Figure 6: Load-Displacement relationships of tested models and FE model from ABAQUS.

The specimens No. 2 and No. 3 presented a deformation in the cross-section of the external coupler. Before the application of the load, the piles present a perfect circular cross-section. When the load starts to be applied and reaches a value higher than 2700 kN (since the cross-section of specimen 1 remained unaltered) the circular cross-section turns into an oval-shape. Figure 7 shows the deformations observed in each one of these specimens.

5.2 FE Analysis

The analysis of the mechanical connection is performed using the FE software ABQUS. The two steps mentioned before reproduced identically what is conducted in the experimental tests. The load-displacement relationship obtained by this model is plotted in the same chart where the tests are plotted (figure 6). In this plot, the initial displacement of the system is deducted from the overall displacement. This is done to retrieve the information of the load capacity of the system after the engagement of the pins with the piles.

A second set of results is plotted in figure 8. This chart shows the Von Mises stress (VMS) with respect to the reaction force caused by the displacement of the lead pile. It is clearly seen that the first areas to reach their ultimate capacity are the holes in the external coupler, followed by the holes in the lead pile. The higher capacity of the lead pile be assumed to happen due to the confinement condition of the lead pile. As figure

9c suggests, the pins are under bending stresses and the most critical zones are along them and not in the contact points. However, the pins are not the critical components of the mechanical connection.

Figure 9a and 9b show the zones where the highest stresses occur in the piles. The areas surrounding the holes are the most critical ones and the stress does not propagate through the whole pile. It can be seen that the deformations correspond to the deformations in the experimental tests. These results represent the validation of the model.

(a) (b) (c) (d)

Figure 7: (a) Deformations on holes of external coupler in specimen 1, (b) ovalized cross-section in specimen 2, (c) block shear failure in specimen 2, (d) deformation of external coupler in specimen 3.

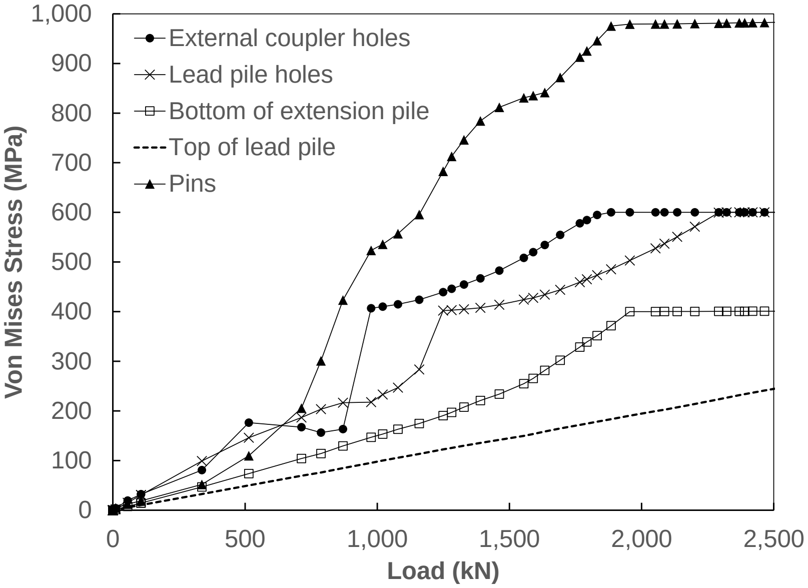
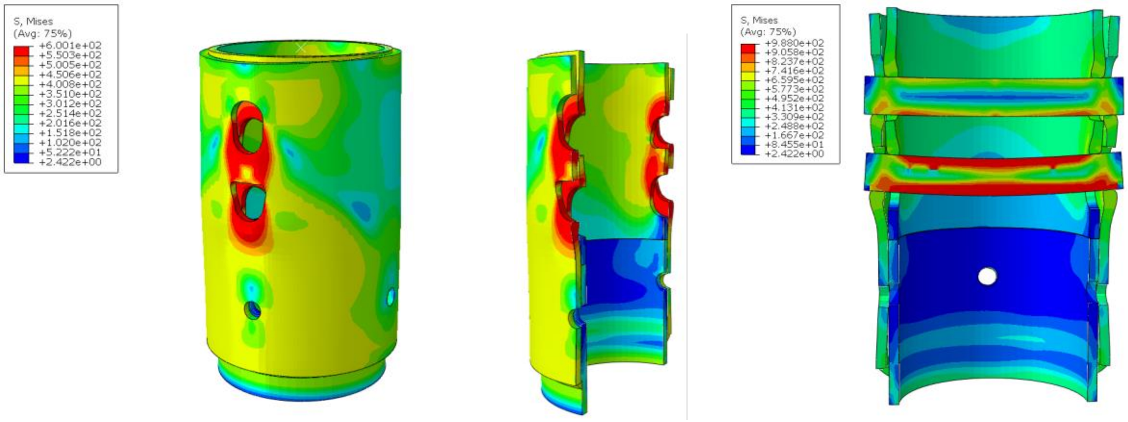


Figure 8: Von Mises stress – Load relationship.

6 CONCLUSIONS

A Finite Element (FE) model was developed to accurately predict the compressive response of the mechanical connection used in steel helical piles. The created model was compared with the results obtained from three experimental tests conducted in this study. The geometry of the components in the model, the material properties, and loading and boundary conditions, were perfectly reproduced in the model as per the ones in the experimental tests.



(a) (b) (c)

Figure 9: (a) VMS in external coupler (b) Vertical cut of the assembly showing the VMS in all the piles (c) VMS in pins.

The following are the conclusions found after the finite element analysis was conducted:

- The holes in the external coupler and the lead pile are found to be the most critical zones of the mechanical connection. These findings correspond to both the experimental test and the FE model.
- The overall compressive capacity of the mechanical connector relies on the capacity of the areas around the holes in the external coupler.
- The yielding capacity of 400 MPa of the material surrounding the holes in the external coupler was reached when the load applied was 1000 kN.
- The deformation of the holes in the lead pile and external coupler are very similar. This is only in the case where both of the components present the same wall thickness. However, the holes in the lead pile tend to be stiffer due to the confinement provided by the external coupler.
- The pins presented bending deformations when subject to a compressive axial load close to 3000 kN. However, the deformations of the holes in both pile and coupler are large enough to consider the pins not critical.
- Ovalization of the cross-section of the external coupler was observed. This effect occurs due to the unconfined condition of this component. A small ovalization of the cross-section is observed with a load higher than 2700 kN. However, this deformation is not critical due to the lower capacity of the holes.

Acknowledgments

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