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NUMERICAL AND EXPERIMENTAL STUDY OF A NEW TYPE OF CLIP FOR JOINING CABLES.

D. Castro-Fresno[1], J. J. del Coz Díaz[2], M. Alonso Martínez[1], E. Blanco-Fernandez[1] y J. A. Polanco Madrazo[3]

[1] *GITECO Research Group, ETSICCP, University of Cantabria, 39005 Santander (Spain)*

[2] *Department of Construction, EPSIII, University of Oviedo, 33204 Gijón (Spain)*

[3] *LADICIM Laboratory, ETSICCP, University of Cantabria, 39005 Santander (Spain)*

Abstract

This paper details the design of a new metallic cable-joining clip for slope stabilization nets. The main objective of this research paper is to numerically and experimentally analyze the resistance capacity of a new clip model for cables with diameters of 8 and 10 mm. Firstly, laboratory tests are performed on the clip and the cable. Then, the clip performance during opening and displacement tests is simulated through a nonlinear finite element model. In the simulation, the different geometrical shapes are included, taking into account plasticity, large displacements and frictional contacts between cable and clip. Thirdly, an optimization is carried out based on a design-of-experiments (DOE) statistical technique, with the aim of adjusting the mathematical model to the experimental results and examining the influence of the most important parameters. With this method, good results in terms of deformation and resistance have been obtained with the numerical and experimental models. This analogy helps to extrapolate the results to other non-tested clips that share a basic group of constant parameters. Finally, the most relevant conclusions as well as future lines of research are presented.

Keywords: Cable nets, Clips, Nonlinear Simulation and contacts, Structural Test, optimization based on DOE.

Research highlights:

► Structural assessment using sophisticated non-linear finite element models and experiments.

► Search for optimal value based on the design of experiments and sensitivity analysis.

► Numerical model of cable nets including a detailed contact-frictional model between clips and cables.

► Experimental validation of nonlinear numerical models.

1. INTRODUCTION

When carrying out road works, there is the important problem of slope instability. This problem is even more serious in areas such as Northern Spain, where geography is highly irregular and climatic conditions erode soils and rocks. For this reason, public administrations and civil engineering companies look for solutions to mitigate the effect of landslide on roads. In fact, for a long time the GITECO group (Construction Technology Research Group) together with interested companies has been working with cable nets to improve the existing systems. This paper is a product of these projects in collaboration with the University of Oviedo.
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The use of cable nets to stabilize slopes offers a structurally discrete solution. The grid net of finite longitude elements must bear the loads generated by the terrain. The simulation of cable-joining elements by the finite element method (FEM) helps to provide information about the stresses in the clips, in relation to the cable diameters and the direction of loads applied.

This work analyzes the performance of the elements joining the cables in a net. A new type of joining, the clip, was designed, and using the finite element method it was simulated. This choice of method was made based on previous experiences in which it was found to be a good method for singular structures. In the simulated model it is verified that when tensile loads are applied to the cables, some responses are produced in the structural elements joining them. The numerical model was validated by means of previously-performed laboratory experiments. The relevance of the behavior of the clip joining the cables in the net led on to study and model numerically a new type of clip. In fact, FEM helped in the structural design and analysis of the new clip type without increasing the costs.

In previous papers [1-4], cable nets had been analyzed by nonlinear FEM simulations. A model was created and validated later with experimental tests. At that time, tests were carried out on a new element of cable joining in nets, but the performance was neither simulated nor analyzed.

Structural analysis of joining systems is a very important research field today. In Sweden, the Department of Aeronautical and Vehicle Engineering developed a computational model to predict the stress distribution in sheet steel joining [8]. This model was developed with FEM based on structural elements. In our case, a similar numerical method was used for a completely different type of joint: a model of clip to join the cables in the net.

Concerning cable nets, there are many papers studying them. In the University of Keio (Yokohama, Japan) studies of membranes made of cables were carried out [5]. They were simulated by finite elements and the influence of the displacement of the net nodes was studied. In turn, the University of Cantabria also developed work previous to this on cable nets in collaboration with a private company which manufactures them [2,4]. All these papers highlight the net bearing capacity and the relevance of its response. This research paper focuses on the cable joinings, which have been ignored in the literature until now.

The authors´ experience in the field of simulation and non-linear model analysis has supported this work. For years, different finite element studies have been carried out and it has been verified that the method achieves good results when the models are correctly validated [1-4,6-7].

2. THE SYSTEM AND THE CLIP DESIGN

Cable nets are made of metallic ropes joined forming a mesh. This system is then anchored to the ground by bolts. To select the most suitable net, it is necessary to know the load that the ground (either soil or rock) will apply on the net during its useful life. This load is calculated using different well-known methods such as limit equilibrium or finite elements, but can also be calculated by means of dynamic simulations [9]. Starting from the load value obtained, the necessary characteristics of the net components, such as the cables, clips and the bolts, are calculated.

In this work, a new clip model that joins two cables which cross is designed. When a cable net is working, some stresses are produced in its elements, cables tighten and clips must have high stiffness to avoid elements moving freely. The joint of two cables in the net is very important in the overall operation, because if the point where the two cables join moves freely, the net grid size increases and the system fails, causing landslides to fall onto roads. The new joint model presented herein guarantees that the net grid is maintained valid when two cables cross and that it is able to bear the loads that tend to move one cable over the other.

Apart from the working conditions, the following influential factors must be considered in the clip design:

- Shear on the cable: the load applied on the clip to keep the cables attached can damage them reducing their bearing capacity.
- Interlocking among nets: clips must not have protuberances or sharp elements which may damage workers or other nets.
- Brittle or ductile fracture: the material properties and the clip geometry must bear loads. Failure due to breaking or opening of a clip gives rise to an important loss of resistance in the net.
- Oxidation: the materials are metallic and environmental conditions are unfavorable, which produces oxidation. Oxidation diminishes the elements' resistance properties, reducing their durability.

The cable joints presented here had never previously been tested, so their performance within the cable net was unknown. Although this type of joint is important, there were no detailed studies on them. For this reason, a new model of cable joint, the clip, was designed.

For the design of the new clip, different choices have been proposed. A prototype at scale 1:1 was made for each one and later they were tested in the lab (see Fig.1). The different models were analyzed to verify the fulfillment of their functional requirements concerning resistance and deformation, as well as to evaluate manufacturing and other associated costs.

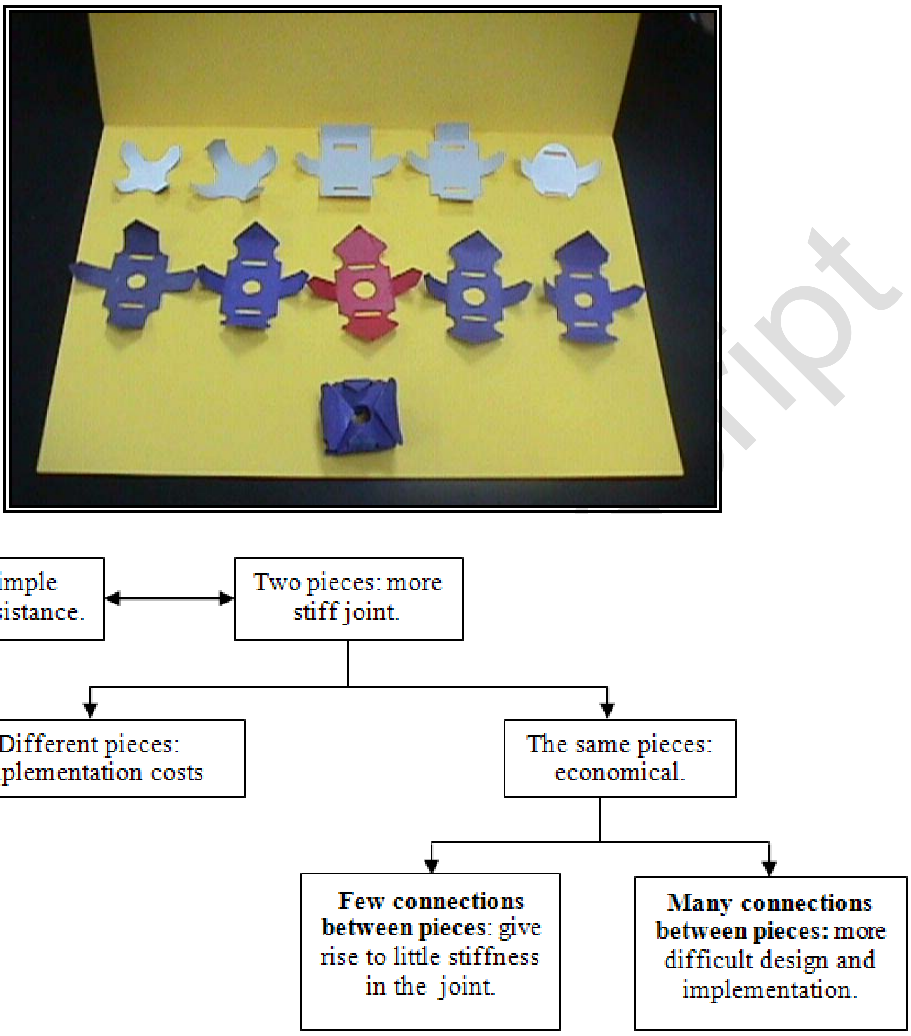


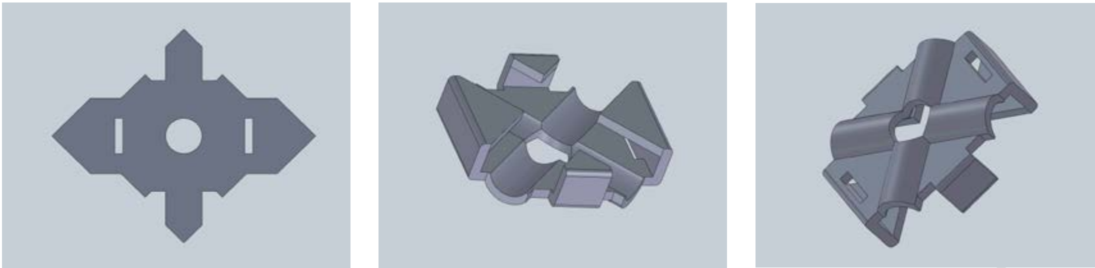
Figure 1: Different models of design choices (upper) and diagram for the study of the new clip (lower).

The same clip model is designed for two different cable diameters: 8 and 10 mm size. The geometrical model is parametrically set up in order to change the size maintaining an identical geometry.

The different designs must guarantee that the systems' working conditions are fulfilled, as well as parameters related to implementation, durability and associated costs.

The aspects assessed in the different choices are shown in the diagram in Fig.1.

Finally, the choice of optimal solution was a clip made of two identical pieces joined by four pins each. These pins are folded and inserted into the opposite symmetrical piece, thus enclosing and protecting the two crossed cables. With this model, a joint is achieved that is stiff, strong and without sharp elements. In consequence, the proposed objectives are fulfilled (see Fig.2).



a) **b)** **c)**

d) **e)**

Figure 2: Clip details: (a) model before folding; (b) isometric lower view; (c) isometric upper view; (d) assembled clip and (e) final assembly with cables.

Figs. 2a, 2b and 2c show the final model of piece of the clip in two stages: before folding and folded. Figs. 2d and 2e show the metallic pieces making up the assembled two-clip joint, and the clip joint in a cable net.

Figure 3: Actual application: cables and clips joints in a net over a road slope.

Figure 3 shows an actual cable net application in a slope. It is possible to observe the importance of the system in order to avoid the objects fallen in the road.

3. LABORATORY TESTS.

Structural tests were performed in LADICIM, a laboratory belonging to University of Cantabria. LADICIM is accredited by ENAC (Entidad Nacional de Acreditación) according to ISO 17025 to perform a wide range of mechanical test on steel wires and cables, railway sleepers and culvert covers.

The cables and joining elements were tested to establish their structural behavior, with prototypes at 1:1 scale. Thus, the force-displacement diagram was obtained, which enables the verification of the data provided by cable manufacturers and the resistance of the designed joint.

Cable resistance is one of the most important net properties, because it limits the cable net resistance and deformation. To obtain it, the cable is tested with a uniaxial tensile test (see Fig. 4a).

To guarantee the cable jointing and the net function, the clips were tested with a slip test and opening test (see Figs. 4b and 4c, respectively).

These tests are chosen for the following reasons:

- Slip test: the movement of one cable over another in the joints is considered a failure in the system. If an object hits the net and the cables move, the net grid becomes bigger and the system fails. Therefore, the clip must guarantee that there will not be movements in the cables and so, displacement resistance tests were performed (see Fig. 4b).

- Opening test: the clip efficiency is affected by shear forces. This occurs when a tensile load is applied to the net. In this case, the cables that cross the joint must support different loads and, as a consequence, a shear force appears in the joint. For this reason, opening tests were carried out (see Fig. 4c).

These tests were based on joint failure due to sliding of the cables or clip opening, without reaching breaking point.

a) b) c)

Figure 4: Laboratory tests: (a) uniaxial tensile test on cable, b) slip test on clip-cable assembly, (c) opening test on clip-cable assembly.

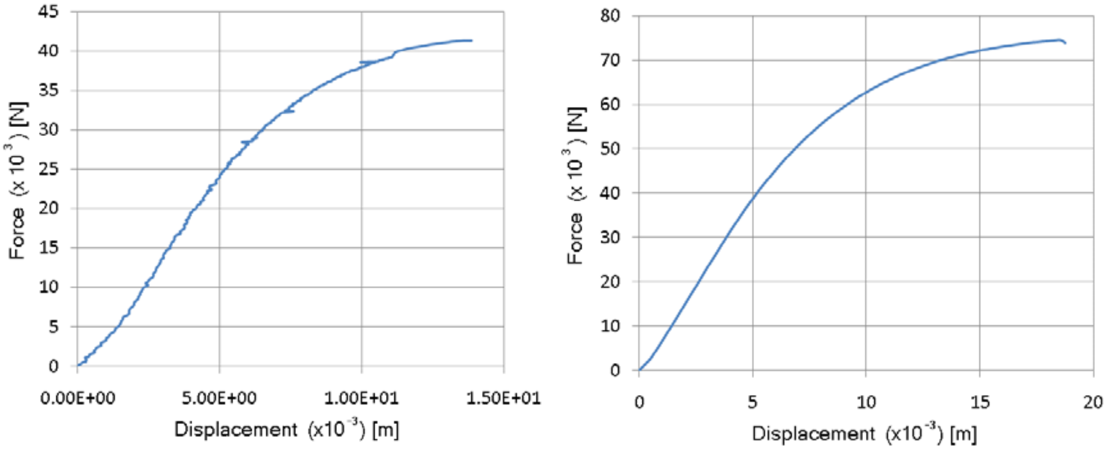
3.1. Tensile test on cable.

The tensile test determines ultimate strength of the cable. To prepare the samples, the cable ends were inserted into a lead tube and they were affixed with resin. This is necessary to hold the cable in the machine clamps when the test is carried out. The cable properties in the tensile test are summarized in Table 1:

Table 1: Tensile properties of the cable.

Cable characteristics	**Diameter 8 mm**	**Diameter 10 mm**
Composition	6x19 + 1	6x19 + 1
Cross section [mm^2]	26.11	40.83
Ultimate Strength [kN]	34.8	54.4
Unitary weight [kg/m]	0.221	0.346
Young´s modulus [Pa]	$1e^{11}$	$9.6e^{10}$

The sample behavior during the test is shown in force-displacement graphs. The relation between the load applied and the cables displacement can be obtained, so the elasto-plastic performance is established (see Fig.5)



a b

Figure 5: Force-displacement graphs obtained in the tensile tests: a) 8mm cable; b) 10mm cable.

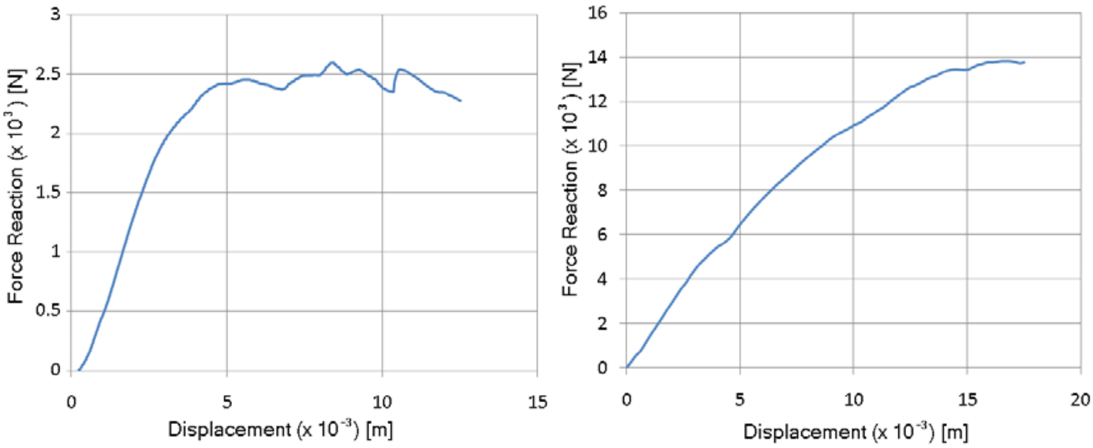
In Fig. 5, a non-linear performance with plasticity in the cable is observed. Therefore, we will use an elasto-plastic material model in the simulations carried out with FEM [2,12].

The uniaxial tensile test of the cable provides information about its resistance, but the net resistance is also determined by the joints response. Therefore, the resistance characteristics of the clip-cable joint will be obtained from the displacement and opening test.

3.2. Slip test

Six samples were tested: three of 8mm diameter cable and another three of 10mm diameter cable. The sample was prepared in the same way as in the uniaxial tensile tests. In this case, the cable-clip joint assembly in the testing machine is: on one side, a short cable is fixed horizontally to the machine with clamps; on the other, the long cable is placed vertically in the short crossing (see Fig. 4b). The machine applies a tensile load on the long cable until one cable is displaced relative to the other.

From these experiments, the displacement of one cable relative to the other is obtained when applying load to opposite ends (see Fig. 6).



a) b)

Figure 6: Force reaction-displacement graph for the slip test: a) 8mm cable; 10mm cable.

3.3. *Opening test*

Like in the previous case, 6 samples are tested, 3 with 8mm cable and 3 with 10mm cable. In this case, the clip joins two cables of the same length and a force is applied to the adjacent ends of the crossed cables (see Fig.4c). The tensile force provokes that the clip open. From this test, the maximum load the joint can bear without opening is obtained for 8 and 10mm cables (see Fig.7).

The system fails when the cables displace, although the clip maintains its mechanical and geometrical integrity throughout the whole process.

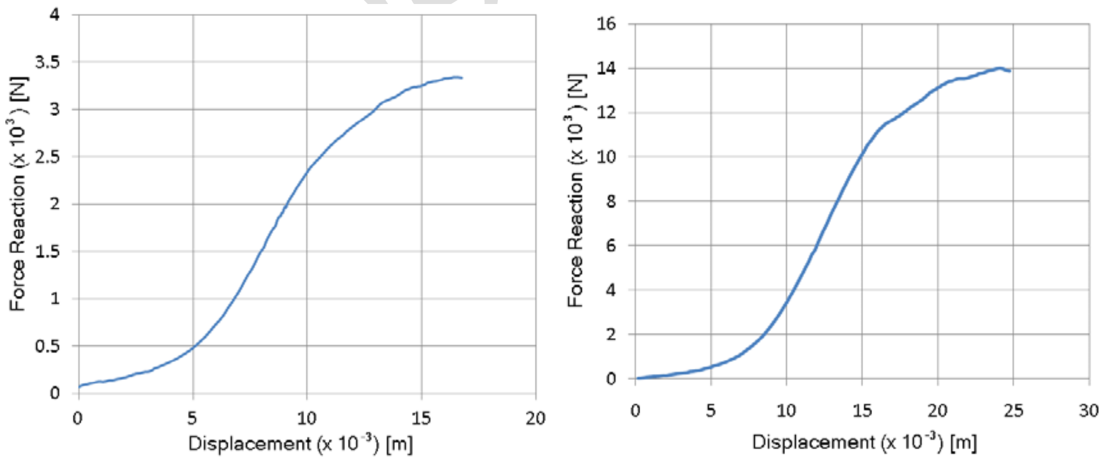


Figure 7: Force-displacement graph for opening test: a) 8mm cable; 10mm cable.

The start of the opening test is unpredictable due to an initial tiny gap between the cable and the clip. In all the tested samples the same curve is obtained displaced along the x axis. The clip-cable set starts to perform as a joint when the elements are assembled.

4. NUMERICAL SIMULATION.

From previous net tests carried out in laboratories [2] it was observed that the failing elements in most cases are the cables and not the joints. However, the cable joints remain an important and unknown factor in most cases. The global failure of the system is produced by a maximum force which opens the clips or slips the cables. It is important to take into account the joint’s performance in the nets to make sure the system fulfills its function. Therefore, numerical analysis is essential.

The numerical simulation carried out in the University of Oviedo used the ANSYS Workbench V 12.1 software. With this simulation technique, the structural response of the basic parts composing the net can be understood in great detail, saving costs and time in relation to tests.

Before the analysis, the new clip design is modeled, including the cables, using the parametric 3D CAD software incorporated in the ANSYS-Workbench environment called Design Modeller.

Four different geometrical models have been devised, both for the displacement and the opening test, with 8 and 10mm cables. From these models, the loads and boundary conditions have been introduced, the solution options have been defined and the models have been numerically solved.

After achieving a FE model able to suitably reproduce real performance, a design study based on the FE model has been carried out. The aim of the new analysis is to assess the most influential parameters on the system’s structural response.

These simulations with a highly non-linear problem, including contacts, plasticity and long displacements, help to bring about a very interesting research problem for the reader.

4.1. Finite Element Model

In this work, the FE model has been based on the following:

- Types of finite elements: In this simulation, two types of solid finite elements called SOLID186 and SOLID187 have been used. These elements are suitable to model irregular nets, such as those needed for geometries imported from CAD/CAM systems. The SOLID186 is a higher order, 3-D, 20-node solid that exhibits quadratic displacement performance and is defined by 20 nodes having three degrees of freedom per node: translations in the x, y, and z directions. The SOLID187 tetrahedral solid element is a higher order, 10-node element with quadratic displacement behavior and is well suited to modeling irregular nets. We have used SOLID186 element for the cables and SOLID187 for the clips.
- Material properties: In this simulation, two material models are defined: a bilinear plasticity model for the clips and a multilinear model for steel used in the cable, both with isotropic hardening. The corresponding characteristics are summarized in Table 2. Moreover, the different tensile and bending

performances have been considered, so the values of the material properties have been modified according to Table 2.

Table 2: Material Properties

	Steel clips	**Cable 8mm**		**Cable 10mm**	
		Displacem.	**Opening**	**Displacem.**	**Opening**
Poisson´s ratio	0.3	0.3	0.3	0.3	0.3
Elastic modulus [Pa]	$2{\cdot}10^{11}$	$1.2{\cdot}10^{11}$	$5{\cdot}10^{10}$	$9.5{\cdot}10^{10}$	$8{\cdot}10^{10}$
Elastic limit [Pa]	$3.75{\cdot}10^{8}$	$9{\cdot}10^{8}$	$5{\cdot}10^{8}$	$1.08{\cdot}10^{9}$	$1{\cdot}10^{9}$

- Contact properties: With the aim of reliably reproducing the existing relations between the clip and the cable, a contact model has been used between the two. On the one hand, contacts are modeled with friction through the “Augmented Lagrange” algorithm between the clip and the cable and on the other, bonded type contact is modeled through the “Pure Penalty” algorithm (see Figs. 10a and 11a). Other contact characteristics are:

    - Contact stiffness factor: 0.01 (relationship between the elastic modulus of cable and clip).
    - The contact stiffness was updated after each equilibrium iteration.
    - We have used the contact-pair finite elements named Contact 174 and Target 170.
    - The initial friction coefficient considered in this work was 0.5 and, in consequence, an unsymmetric stiffness matrix has been taking into account in the numerical simulations.

- Geometry mesh: the geometrical models are meshed by a hex-dominant method, differentiating two bodies: the clip and the cable. Symmetrical pieces composing the clip are more finely meshed, while a coarser mesh is used for the cable (see Figs 8a, 8b, 9a and 9b). Furthermore, the mesh quality has been analyzed and the aspect ratio results are show in Figs. 8c, 8d, 9c and 9d.

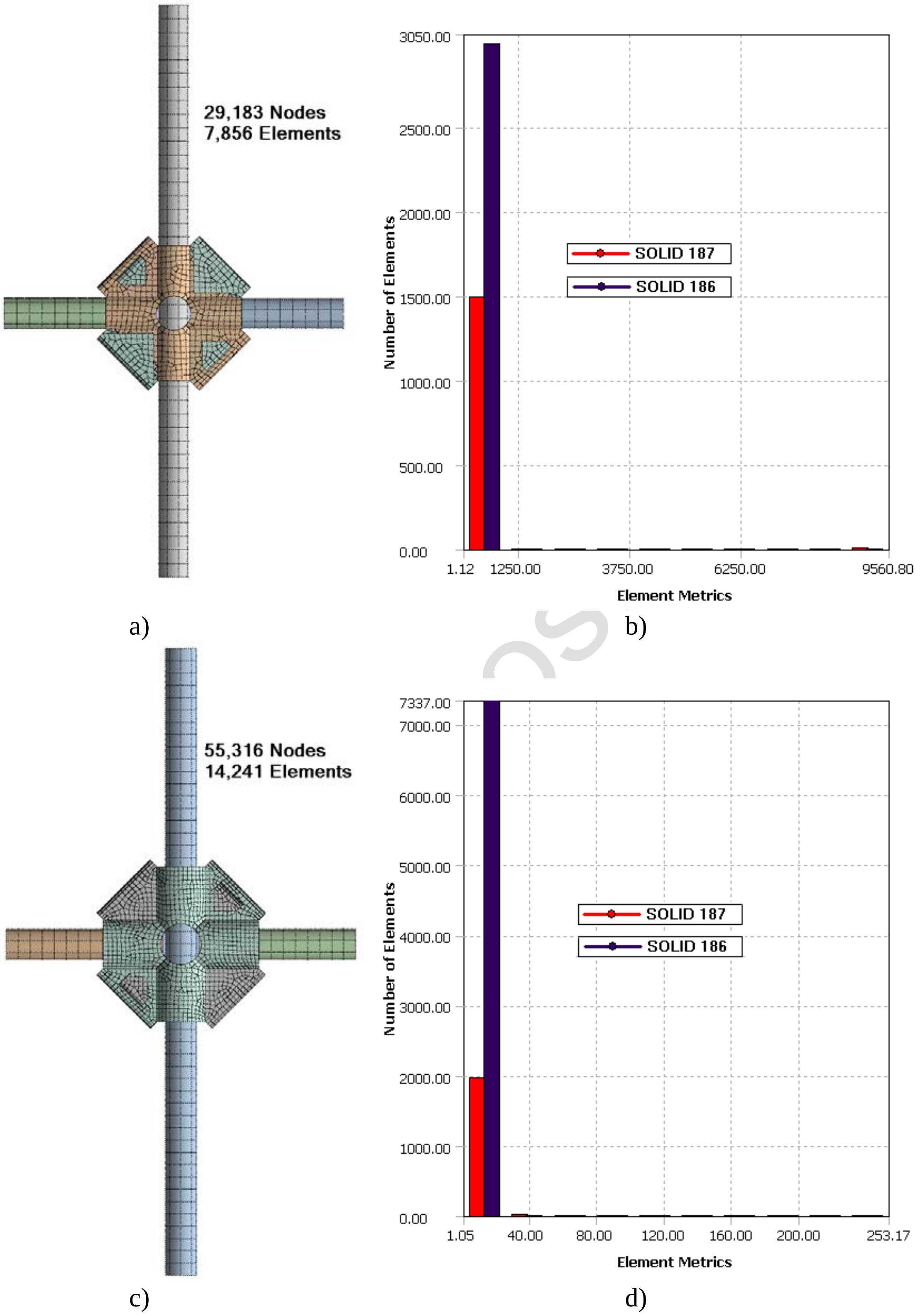


Figure 8: FEM mesh and aspect ratio quality for slip tests: a) 8mm. cable b) 10mm. cable

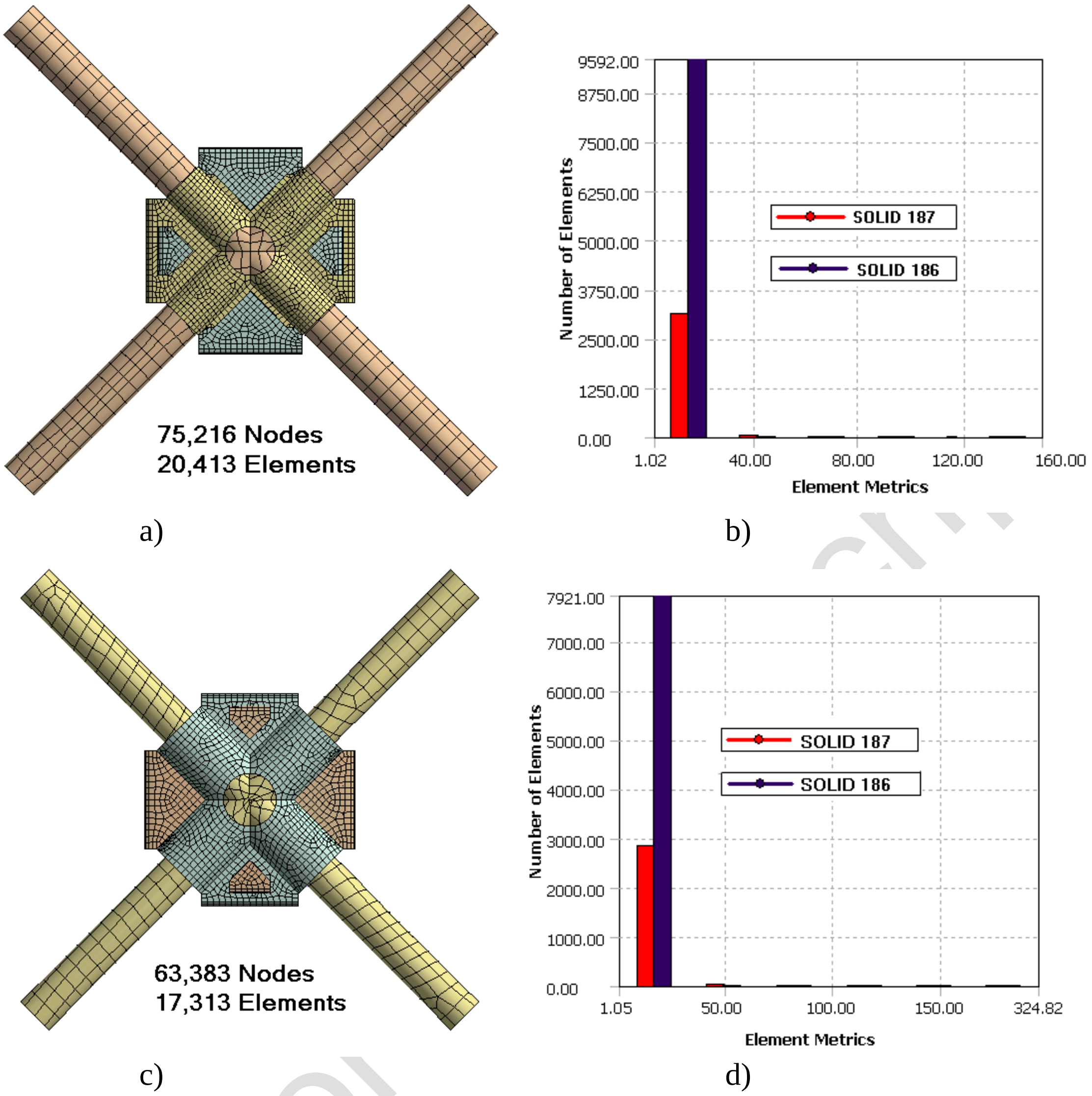
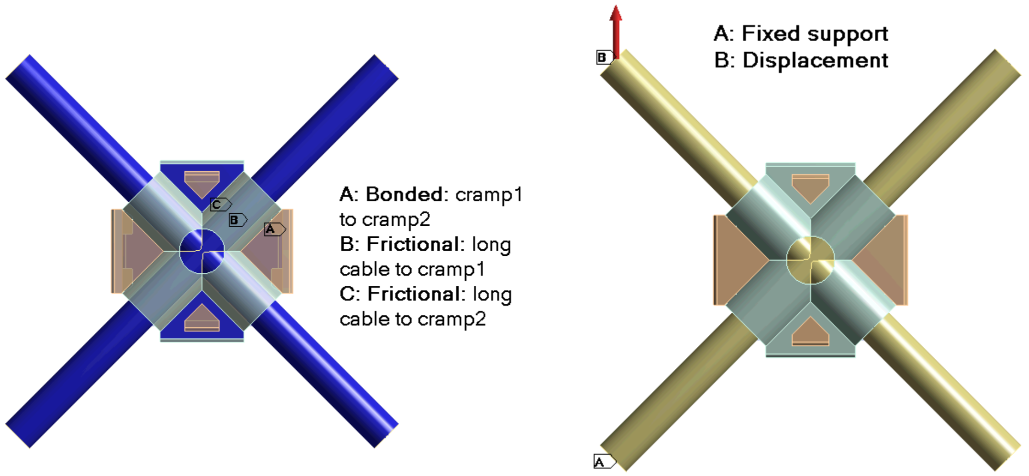


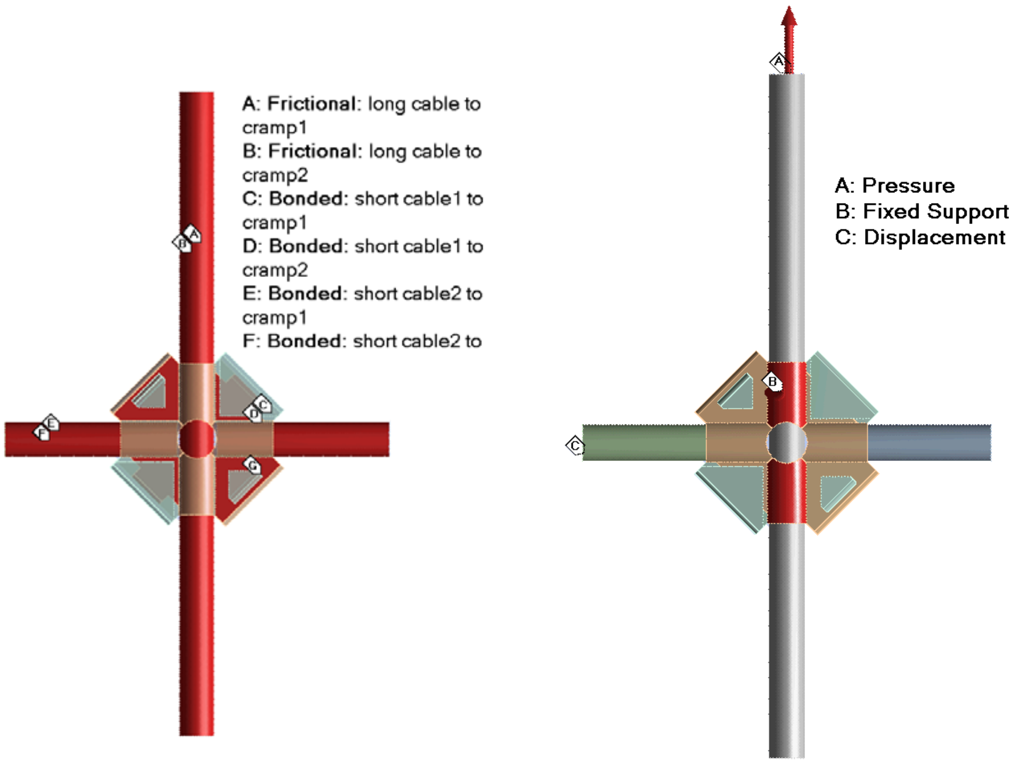
Figure 9: FEM mesh and aspect ratio quality for opening tests: a) and b) 8mm. cable; c) and d) 10mm. cable

- Boundary conditions: the conditions imposed on this simulation reproduce the clips' performance in the testing machine, so fixed supports are used. These constraints are placed depending on the type of test to be simulated, differentiating the uniaxial tensile test and the opening or displacement tests (see Figs. 10 and 11).



a) b)

Figure 10: Boundary and contact conditions in the opening test model: a) contacts; b) applied loads.



a) b)

Figure 11: Boundary and contact conditions in the slip test model: a) contacts; applied loads.

Stress on the model: for both tests, the displacements imposed by the testing machine on the joints have been introduced. As well as the pressure in the clip which have been applied to displacement tests. The values of these loads are shown in Table 3:

Table 3: Loads considered on the simulated models.

	Displacement tests		Opening tests	
	8 mm Cable	**10 mm**	**8 mm Cable**	**10 mm Cable**
Pressure between clips [MPa]	9.5	23	-	-
Applied displacement [mm]	12	20	12	18

- In the opening tests a progressive displacement is applied, which triggers the cables' deformation and the clip opening. In the slip test a pressure is applied in the middle of the clip and a displacement is applied in one of the vertical cable ends (see Figs. 10b and 11b).

The present nonlinear structural problem was solved by the full Newton-Raphson option for all degrees of freedom with an unsymmetrical solver including the adaptive descent option. With the aim of achieving an initial solution for the contacts' state, it was necessary to perform two loading steps: an initial one in which a tiny initial displacement is applied and another one in which the full displacement is applied. The Newton-Raphson analysis options for a time step of 1 second, discarding the inertial effects, were as follows:

Table 4: Newton-Raphson analysis options for a time step of 1 second.

	Displacement		**Opening**	
	8 mm Cable	**10 mm Cable**	**8 mm Cable**	**10 mm Cable**
Initial Time Step [s]	0.1	0.1	0.02	0.1
Min Time Step [s]	0.1	0.05	0.01	0.05
Max Time Step [s]	0.2	0.2	0.1	0.1

In order to stabilise the solution, a force tolerance value of 0.5% was considered with a minimum value of 0.01 [N].

The simulation was carried out on a 16-core 2.7 GHz Intel Xeon E5520 processor, with 32 GB of RAM and 8 TB of hard drive. The total CPU time in each load case varied from 2,000 to 8,000 seconds for the displacement tests and from 29,000 to 31,000 seconds for the opening tests.

4.2. Numerical simulation based on Design of Experiments

With the aim of studying the influence of the most relevant parameters on the structural non-linear system performance, a numerical simulation through the DOE technique was carried out based on the FE model previously described.

The most relevant parameters considered and their variation range depends on the test type. These are shown in Table 5.

Table 5: Parameters considered in the DOE.

Test types	**Input parameters**	**Output parameters**
Displacement	Friction clip cable.	Reaction strength
	Force on clip	Error with respect to test
	Reference tension	
Opening	Young's modulus of Cable	Reaction
	Plastic deformation	

The parameter limits are chosen starting from experimental data and previous experiences, for a test design of the *central composite design* (CCD) type. Using the DOE method, structural response surfaces are generated in which the effects provoked by the input parameters can be seen. In this way, it is possible to obtain the optimal values of the parameters considered in the simulation and the reactions within the clip into their variation range.

The parameters considered in each test, as well as the results obtained, are shown next for each test.

4.2.1. DOE for displacement tests.

The input parameters considered in the optimization of the displacement tests are shown in Table 6.

Table 6: Input parameters for the displacement tests.

	8 mm Cable			**10 mm Cable**		
	Minimum	**Initial**	**Maximum**	**Minimum**	**Initial**	**Maximum**
Friction coefficient	0.45	0.5	0.55	0.45	0.5	0.55
Pressure [MPa]	9	9.5	10	21	23	25

The influence exerted by each of the factors is shown in the sensitivity study in Fig.12.

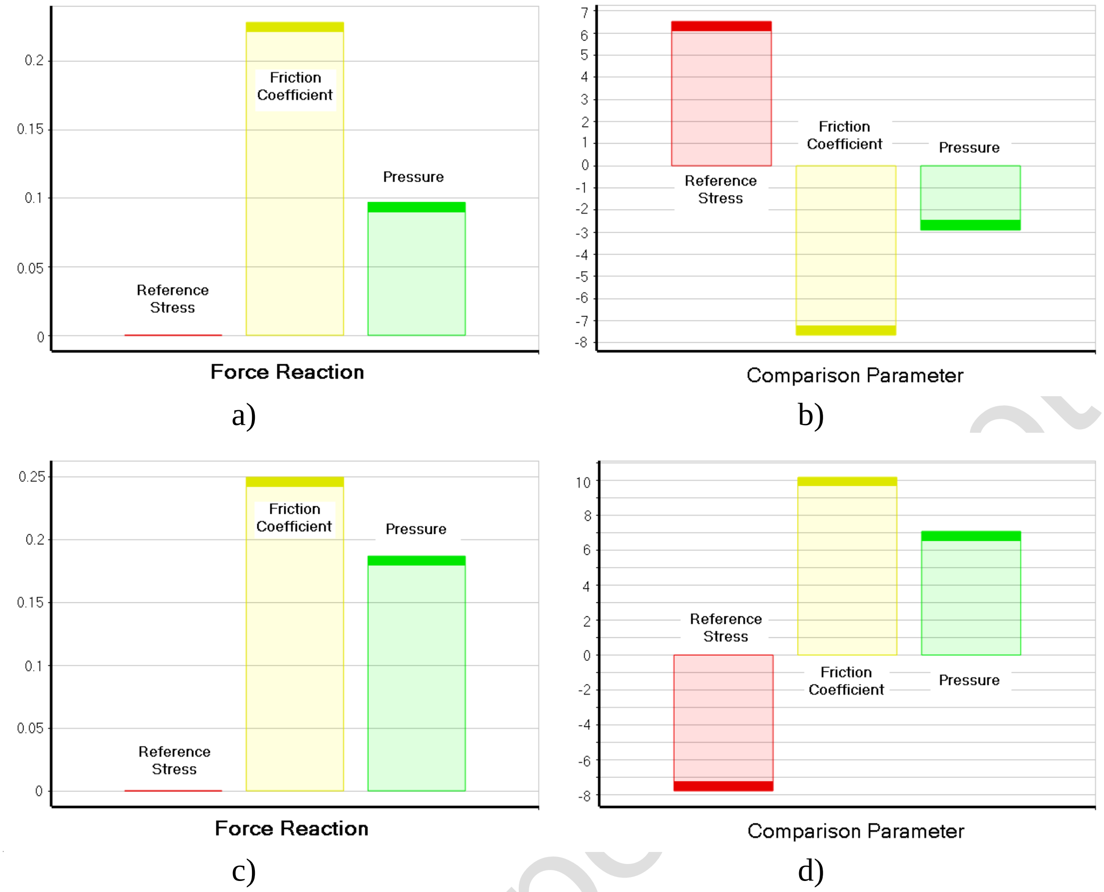


Figure 12: Sensitivity study in the displacement tests of 8 and10mm cables: for 8mm cables (above) a) Reaction force and b) Error with respect to the test; for 10mm cables (below) c) Reaction force and d) Error with respect to the test.

4.2.2. Opening test DOE

In the case of the opening tests, the DOE analysis is carried out taking into account the cable properties as input parameters, because it is known that the cable resistance and deformation are highly influential in the clip performance in the shear test. In this way, the variation of the studied starting parameters is shown in Table 7:

Table 7: Starting parameters for opening tests.

	Cable 8 mm			**Cable 10 mm**		
	Minimum	**Initial**	**Maximum**	**Minimum**	**Initial**	**Maximum**
Young's Modulus [Pa]	$4.4 \cdot 10^{10}$	$5 \cdot 10^{10}$	$5.5 \cdot 10^{10}$	$7.2 \cdot 10^{10}$	$8 \cdot 10^{10}$	$8.8 \cdot 10^{10}$
Yield Strength [Pa]	$4 \cdot 10^{8}$	$5 \cdot 10^{8}$	$5 \cdot 10^{8}$	$9.5 \cdot 10^{8}$	$1 \cdot 10^{9}$	$1.5 \cdot 10^{9}$

The influence exerted by each of the factors is shown in the sensitivity study in Fig. 13.

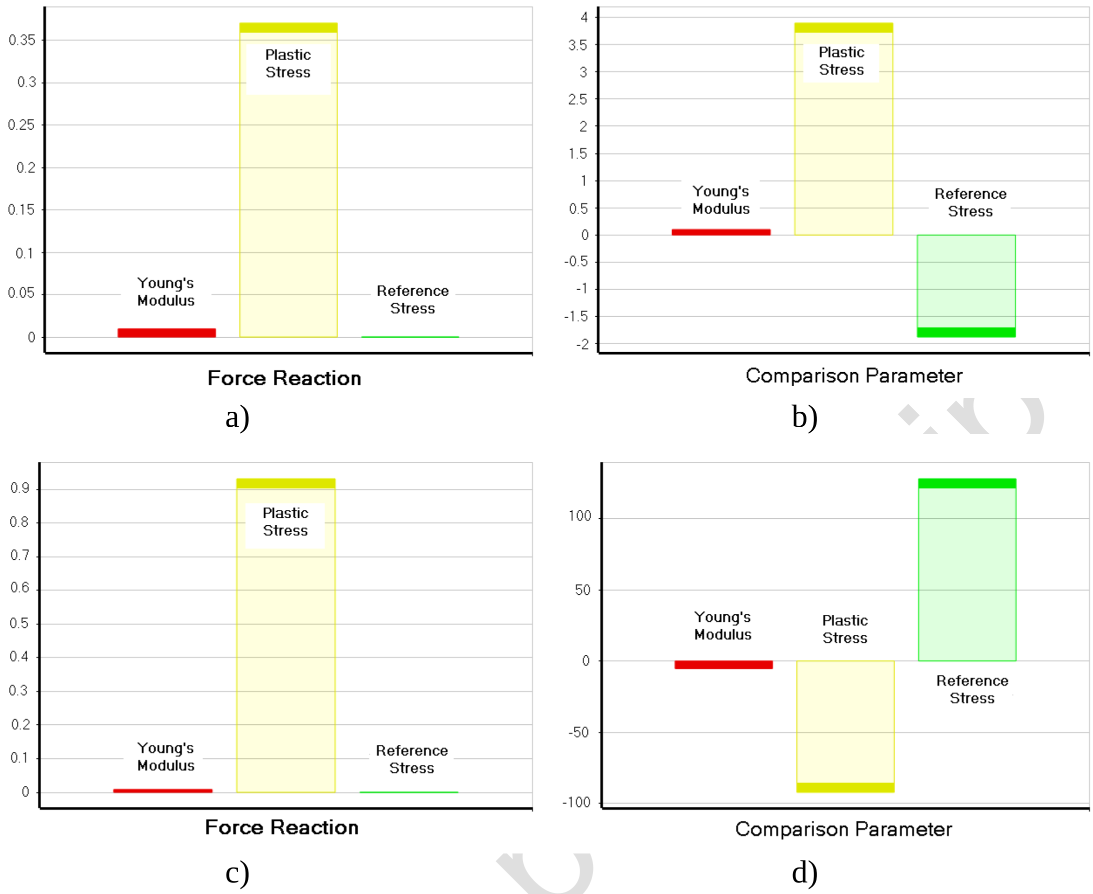


Figure 13: Sensitivity study of the opening tests: for 8mm cables (above) :a) Reaction and b) Error with respect to the test; for 10mm cables (below): c) Force reaction and d) Error with respect to the test.

5. NUMERICAL RESULTS AND EXPERIMENTAL COMPARISON.

In this section, the most relevant numerical results, both of finite elements and test designs are presented. Finally, the experimental results are compared with the numerically deduced ones.

From the results obtained in the slip simulation, the reaction in the lateral supports is measured, in relation to the deformation suffered by the cable. In the analysis of the results, it can be observed that the reaction force increases notably when the cable starts to displace and then remains the same as the displacement extends, as a consequence of the appearance of non-linear phenomena, due to plasticity and contacts.

From the results of the opening simulation, the deformation suffered by the clip when a load is applied on two adjacent cables is measured. From these results, it can be deduced that there is an initial time in which the force on the clip increases more rapidly. This is due to the readjustment of the cable inside the clip when the cable starts to displace.

5.1. FEM results.

The results of the Von Mises yield criterion are shown for the different models (see Fig. 14) along with the results of the pressures in the contacts between the cable and the clip (see Fig.15).

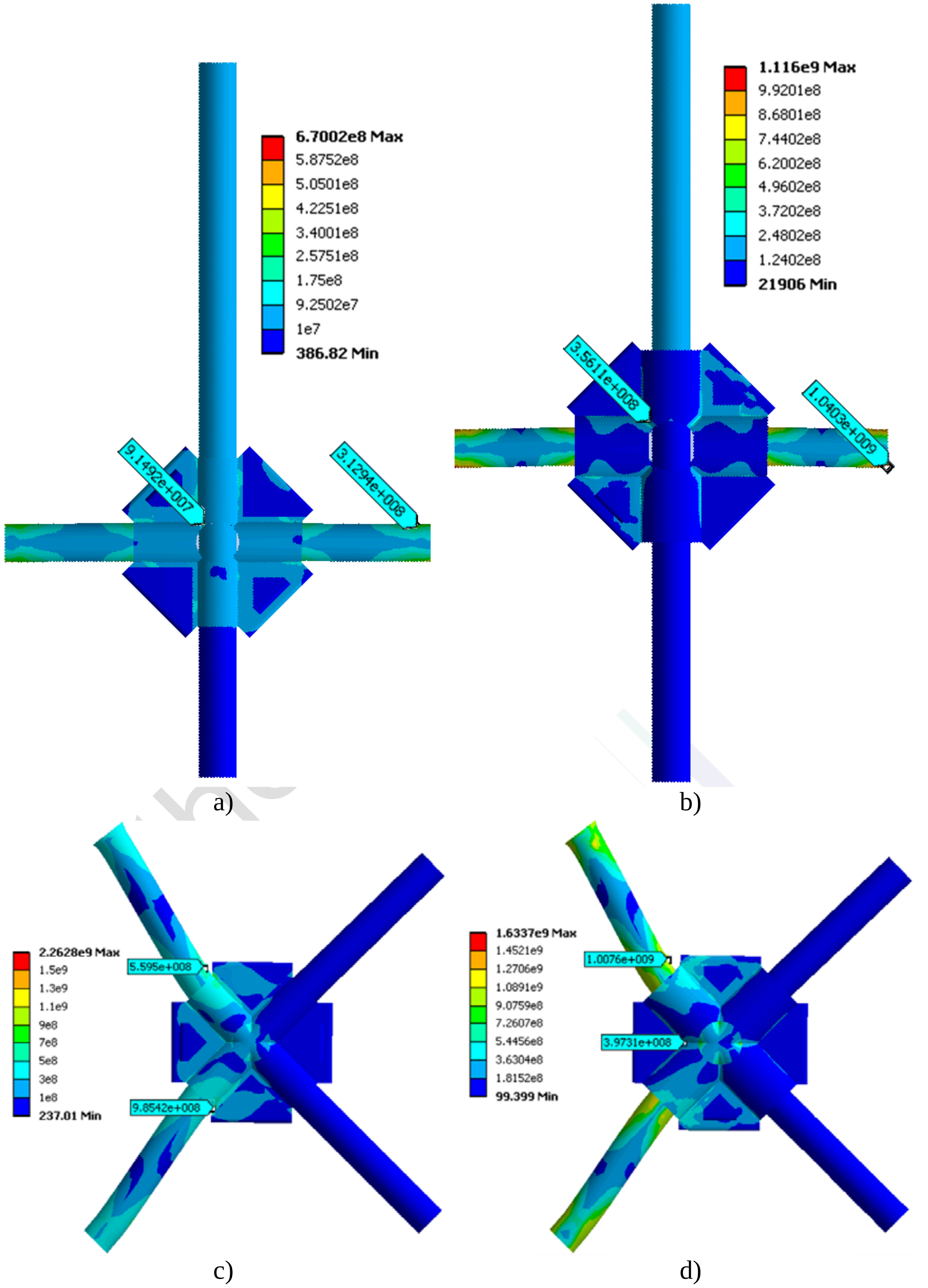


Figure 14: Results of the equivalent Von Mises yield criterion in the numerical simulations: displacement (above) a) for 8mm cable and b) 10mm cable; opening (below): c) 8mm cable and d) 10mm cable.

In Fig.14 (a) and (b) the results of the yields obtained in the slip numerical simulations are shown. Maximum values of yields are observed in the 8mm cable around $3.2 \cdot 10^8$ [Pa] and of the order of 10^9 [Pa] for the 10mm cable. In the clips, maximum yield values of $9.1 \cdot 10^7$ [Pa] for 8mm and of $3.6 \cdot 10^8$ [Pa] for 10mm are observed.

Furthermore, in Fig. 14 (c) and (d) the opening numerical results are seen, where yields in the cable of $5.6 \cdot 10^8$ [Pa] for 8mm and 10^9 [Pa] for 10mm are observed. In the clips, the yields are $9.8 \cdot 10^8$ [Pa] for 8mm and $3.97 \cdot 10^8$ [Pa] for 10mm.

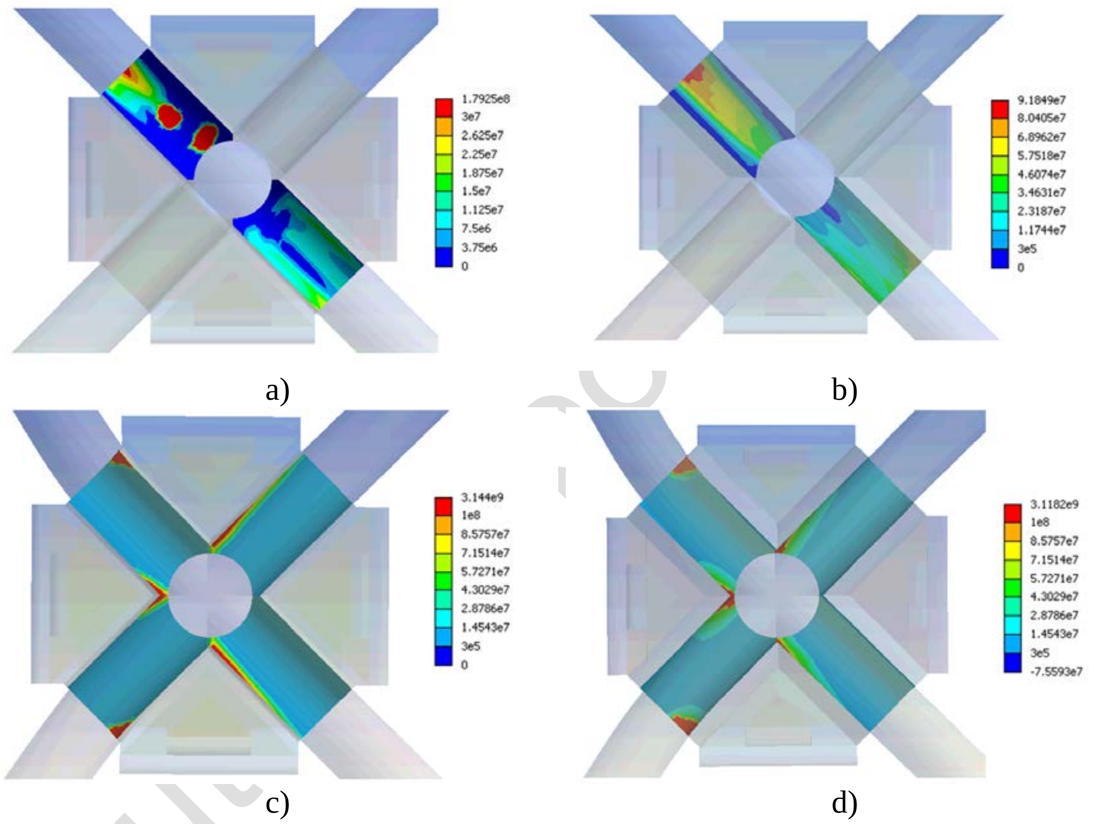


Figure 15: Results of the pressure in the friction contacts between the cable and the clip: displacement (above) a) 8mm cable and b) 10mm cable; c) opening for 8mm cable; d) opening for10mm cable.

The pressure results in the friction contact between the cable and the clip obtained in the numerical simulations of displacement are shown in Fig.15 (a) and (b). Here, it is observed that the maximum and minimum pressure values between the cable and the clip occur when the joint failure is produced for displacement, reaching values of the order of $1 \cdot 10^7$ to $8 \cdot 10^7$ Pa, distributed along the displacing cable. A higher pressure gradient is observed in the area where the cable displacement is applied.

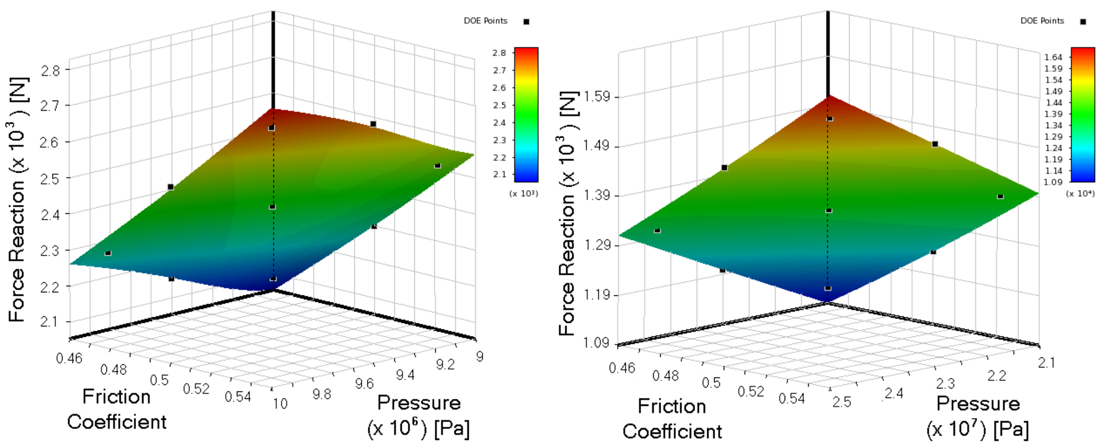
Furthermore, in Fig. 15 (c) and (d), the numerical simulation of opening results can be seen. The pressure distribution in the contact between the cables and the clip can be seen when the joint fails due to opening. In this case, a leverage effect in the cable is observed in corners of the clip, reaching maximum values of the order of $1 \cdot 10^8$ Pa.

5.2. DOE Results.

In this work, the response surfaces for the opening and displacement tests (see Figs. 16 and 17) were obtained. In both cases, the reaction force is taken as an output parameter. The parameters used for both simulations, as well as their values, were shown in Tables 5, 6 and 7. Next, the optimization studies in each of the simulations will be dealt with separately, including their peculiarities.

5.2.1. Slip simulations.

The response surfaces obtained in the DOE analysis for the two clip models in the displacement simulations are shown in Fig. 16. In the graph, the reaction force variation is observed when both the friction coefficient and the applied pressure vary on the clip.



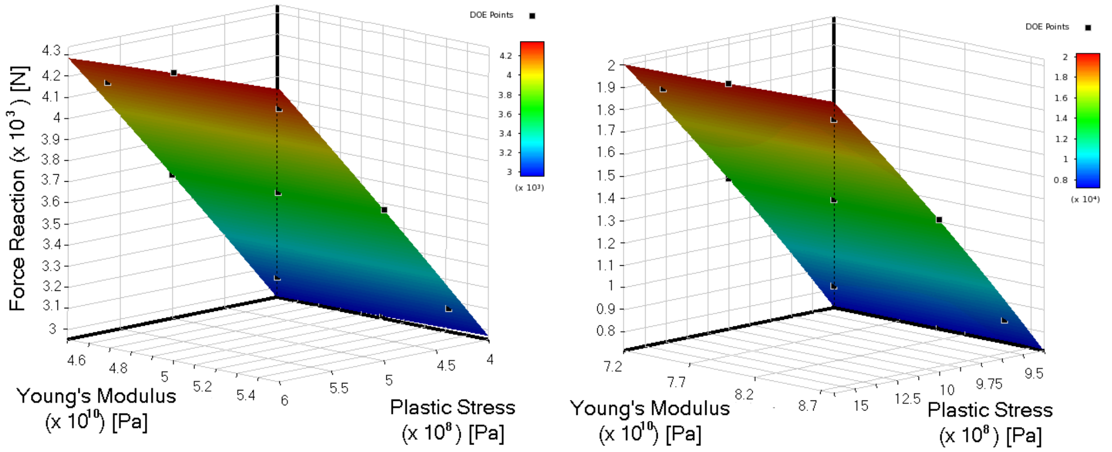
a) b)

Figure 16: Force Reaction results obtained in DOE in the displacement simulations: a) 8mm cable; b) 10mm cable.

In Fig.16 a larger increase in the reaction force is observed when increasing the pressure, as well as a quasi-linear performance in all the variation range studied, for both the 8 and 10mm cable simulations. Thus, it can be concluded that the optimum values will be those obtained with the highest possible friction and pressure values in the joint.

5.2.2. Opening numerical simulations.

The response surfaces obtained in the DOE analysis for the opening numerical simulations can be seen in Fig. 17. The evolution of the reaction force is represented with respect to the two most influential input parameters in this kind of test: elastic modulus and yield or plastic stress. This is known thanks to the sensitivity charts previously shown (see Fig. 13).



a) b)

Figure 17: Results Force Reaction obtained in the opening tests DOE: a) cable 8mm; b) cable 10mm.

In the response surfaces it can be seen that the elastic modulus variation practically does not influence the reaction force in the joint. This is because the cable is undergoing bending stresses, whose elastic limit is smaller than if they were tensile stresses (see Table 2) ; thus, the joint's structural performance is demonstrated to be dominated by plasticity phenomena and large deformations.

5.3. Comparison of numerical and tests results.

The results obtained in the simulation have been graphically compared with those obtained in the lab tests and it can be verified that the two are very similar (see Figs. 18 and 19).

The study of the clip-cable joint is not carried through to breakage, in fact, the aim is to achieve the failure of the joint in both opening and slip simulations.

The comparison of the results in the displacement tests for 8 and 10mm cables is shown in Fig. 18. The comparison of results in the opening tests for both types of cables is also shown in Fig. 19.

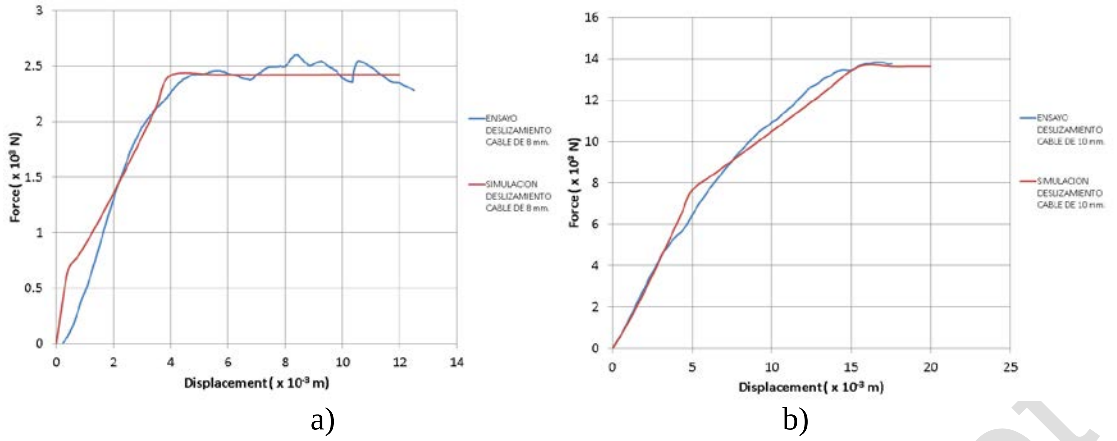


Figure 18 Force-displacement graphs for the slip tests and simulation: a) for 8mm cable; b) 10mm cable.

In Fig. 18, it can be observed that the simulation of the joint failure for slip test displays a good fit with the lab tests. The friction coefficient between the cable and the clip has a great influence on the reaction produced in the clip. This is the parameter that controls the connection stiffness which is represented by the curve's slope. The joint failure is not produced by its breakage, but by the relative cable displacement in the clip. In the final area of the curves, where the slope is null, the friction coefficient changes from being static to being dynamic. In that moment, the relative movement of the cable has started and consequently, the joint failure by displacement is produced.

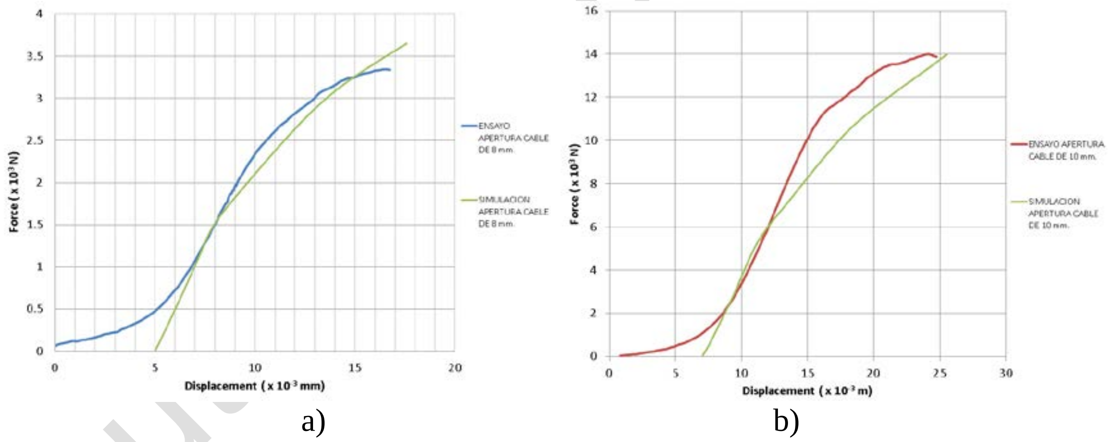


Figure 19: Force-displacement graph for the opening tests: a) 8mm cable; b) 10mm cable. 8mm

The simulation of the opening tests proved to be a remarkable computational challengue due to the complexity it entailed. In this case, the beginning of the test is unpredictable. In Fig. 19, the opening tests carried out in the lab are compared with the opening simulations. In this case, the numerically-obtained force-displacement curve is similar to the real tests, except at the begining of the simulation. This difference is because the real cable has to deform to adjust to the geometry inside the clip due to a tiny initial gap. In spite of the initial uncertainty, the opening tests and the opening simulations have the same deformation speed and a very similar failure value, considering that the failure is the instant in which the clip starts to suffer important opening deformations.

With the aim of reproducing the phenomenon of initial cable adjustment in the clip, we have introduced an initial gap in the contact between the clips and the cables. However, this initial test area was not simulated as it is unpredictable. The joint failure value is obtained from the change in the slope of the force-displacement curve. For this, the curve is fitted to two initial linear sections and the failure is considered to start where the two cross. As can be seen in the images, the results obtained in the simulation are very similar to the experimental tests.

6. CONCLUSIONS

This paper has shown that the use of advanced simulation methods helps to obtain the structural response of a highly non-linear model, such as the one presented.

With the aim of contrasting the numerical and test results, the same conditions have been maintained both in the lab tests and the simulations, so that a contrasted numerical model can be provided. However, in the real situation in service, the cables do not undergo such restricted movements as in the tests and they have more degrees of freedom. As a result, the stresses generated in the simulated system will be smaller than in the tested case, so the joint will be able to bear higher loads before structural failure. However, to achieve this, it will be necessary that the net, its joints and its anchorage elements are arranged under the established conditions.

In the opening test simulations, it was not possible to simulate the test beginning. The joint performance is unpredictable due to the settlement produced between the cable and the interior part of the clip. The addition of an initial gap between the cable and the clip interior offers a partial adaptation of the numerical model to the experimental results. In spite of this, the structural joint’s performance in this test, starting from the moment that the clip-cable assembly starts to work as a unit, is reproduced until failure very precisely.

In general, both in the lab tests and the numerical simulations, the failure is considered to occur at the moment when the joint stops working as such, and in no case is component failure analyzed. This failure, in both the displacement and opening cases, occurs due to a sudden decrease in the force that the joint can bear. Graphically, this failure moment is detected by a loss in stiffness, determined by the slope of the force-displacement curve obtained. In the graphs that compare the experimental and simulated results (see Figs. 18 and 19), it can be verified that the joint failures obtained both experimentally or numerically are very similar. This demonstrates the reliability of the numerical simulations.

Furthermore, the use of a Design of Experiment, DOE, statistical technique has helped in analyzing in detail the joint performance under a wide range of variation of input parameters. Moreover, it has also helped to establish, through the sensitivity analysis, the relative importance of each input variable in the system response, which has in turn enabled the selection of the parameters that best reproduce the joint performance.

In summary, with the proposed method, acceptable results have been obtained, which may be extrapolated to other cases, without entailing an excessive cost increase.

The results encourage future investigation in the field following the same research lines. We will undertake the study of both cable nets and the elements composing them with numerical simulation. In previous works [2] it was concluded that the resistance of simulated cable nets is higher than the resistance of real nets: this is due to the cable joint influence on the assembly's performance. After the analysis of a new joining element in this paper, the objective will be to analyze cable nets with clips by FEM. The authors suggest a future research line to test, simulate and validate the nets including the clips as joining elements. Thus, the study of nets will be continued, including the influence of the cables joining them in the assembly and not just in isolation.

7. ACKNOWLEDGEMENTS

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