METHODOLOGY FOR THE ASSESSMENT OF BOLTED CONNECTIONS BASED ON THE FINITE ELEMENT METHOD AND DATA MINING TECHNIQUES

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Connections between beams and columns are one of the most critical elements in steel structures due to their highly nonlinear behaviour. The failure of a joint would produce the collapse of the whole structure so further details are needed to study geometrical discontinuities, local yielding, contact or stress concentrations.

Nowadays, bolted connections are assessed through the component method which is included in the Eurocode 3. This mechanical method provides step-by-step analytical formulae but do not take into account some of the nonlinearities embodied in the bolted connections. In this paper, an alternative methodology based on the Finite Element Method (FEM) and Data Mining (DM) techniques is presented to predict the fully nonlinear behaviour of bolted connections. This methodology takes advantage of the FEM's capacity but it is capable to reduce the computation time in a simplified mathematical model by means of the DM techniques.

Finally, three cases study focus on the lap joint, the T-stub and the extended end-plate beam-to-column connections have been carried out by EDMANS group in order to apply this novelty methodology. Predictive models have been developed and validated against experimental tests and the results show a high correlation between FE simulations and the predictive models.

Keywords: *Bolted connections; Finite element method; Data mining; Predictive models; T-stub; Extended end-plate connection*

METODOLOGÍA PARA EVALUACIÓN DE UNIONES ATORNILLADAS BASADA EN EL MÉTODO DE LOS ELEMENTOS FINITOS Y TÉCNICAS DE MINERÍA DE DATOS

Las uniones viga-pilar son uno de los puntos críticos en las estructuras de acero debido a su comportamiento altamente no lineal. El fallo de una unión puede provocar el colapso de la estructura completa por lo que resulta necesario un estudio detallado de sus discontinuidades geométricas, plastificaciones locales, contactos o concentraciones de tensiones.

En la actualidad, las uniones atornilladas se calculan mediante el método de los componentes incluido en el Eurocódigo 3. Este modelo mecánico proporciona una formulación analítica que no tiene en cuenta alguna de las no linealidades propias de este tipo de uniones. En este artículo se presenta una metodología alternativa basada en la combinación del Método de los Elementos Finitos y técnicas de Minería de Datos para la predicción del comportamiento no lineal de uniones atornilladas. Esta metodología aprovecha la capacidad de cálculo del FEM pero es capaz de reducir el coste computacional mediante técnicas de minería de datos.

Por último, se describen tres casos de estudio llevados a cabo por el grupo EDMANS con objeto de aplicar la metodología propuesta. Los modelos predictivos generados han sido validados con ensayos experimentales y han mostrado una muy buena correlación con las simulaciones FE.

Palabras clave: *Uniones atornilladas; Método de los elementos finitos; Minería de datos; Modelos predictivos; Unión en T; Unión con chapa de testa extendida*

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1. Introduction

Bolted connections play an essential role in the distribution of the efforts between the structural elements they link. It is not necessary to insist on the importance of those connections because just the failure of a joint could produce the partial or total collapse of the structure. That is why the design of the joints in the construction field must be appropriate. Bolted connections are emerging ahead of the welded joints due to their quickly, safety and economic assembly. In addition, they have an easy control of execution and allow dismantling the structure.

The modeling of bolted connections is highly nonlinear due to several factors such as the contacts, the geometric discontinuities, stress concentrations and plastic modeling, among others. These nonlinearities make difficult to obtain the joint behavior. It also generates difficulties in the task of establishing a reliable method to simulate the structural response of the connection.

Nowadays, the national and international regulations for calculating bolted connections such as CTE and Eurocode 3, are based on an analytical model which is called the *component method.* This method has the advantage of easily obtain the basic parameters of joint behavior. The main drawback is that the models do not provide an accurate response according with the experimental validation.

Other kind of models also exists, such as the empiric ones. That kind of models provides some expressions that have been calibrated using several parameters. Their disadvantage is that the expressions can be only applied to the joint that has been calibrated. Moreover, it is not possible to know which is the importance of the geometrical and mechanical parameters in the joint modeling. The parameters have no physical meaning because they are adjusted by regression. They are also determined through experimental tests that have been previously done.

Experimental models are the most reliable ones because they are based on actual tests which have been carried out in laboratories and have been controlled by rules of a good practice. The main disadvantage of these models is their high cost, so its use is limited. Therefore, that kind of models is only used to validate the results that have been obtained with other models such as analytical, empirical or numerical ones. The large number of tests that have been done all over the world has led to generate several databases. From each test, geometrical and mechanical properties from each joint component are compiled. The main databases that currently exist are the following:

- Goverdhan database. It was the first one to develop (Goverdhan, 1983)
- Nethercot database. (Nethercot, 1985a, 1985b)
- Steel Connection Data Bank (SCDB). (Kishi y Chen, 1986)
- SERICON database. (Gerardy y Schleich, 1991; Weynand, 1992)

The use of databases is very important to validate some models that predict the response of the joint from to its geometrical and mechanical properties. The drawback in the use to design structures is that the probability of finding the joint you wish is very small.

Finally, other type of models is the numerical one. These models can be based on different techniques like the finite element method and they are able to accurately reproduce joint behavior taking into account all types of nonlinearities. The advantages of this technique are considerable; for instance, using this model is able to save costs and to achieve parametric studies with high performance. Bolted connections analysis requires the following parameters (Nethercot and Zandonini, 1990):

- Geometric and material nonlinearities.

- Bolt preloading (Abolmaali et al., 2005; Al-Jabri et al., 2006).
- Interactions between bolts and plates.
- Contacts between the plates in the compression place.
- Sliding between plates.
- Welded connections.
- All types of imperfections.

In spite of the large number of advantages, there are also some drawbacks that make reconsidered the use of this technique in the assessment of bolted connections:

- High computational cost.
- Time spent in the preprocessing and post-processing tasks.

This paper presents a methodology based on the combination of the FEM with DM techniques. All of that greatly simplifies the computation time and the odeling tasks. They also allow us to obtain simplified models that could be included in steel structural softwares.

2. Methodology

Figure 1 shows the methodology layout which comprises the FE model, the experimental validation, the dataset generation and the predictive models. Each part will be briefly explained in the following subsections.

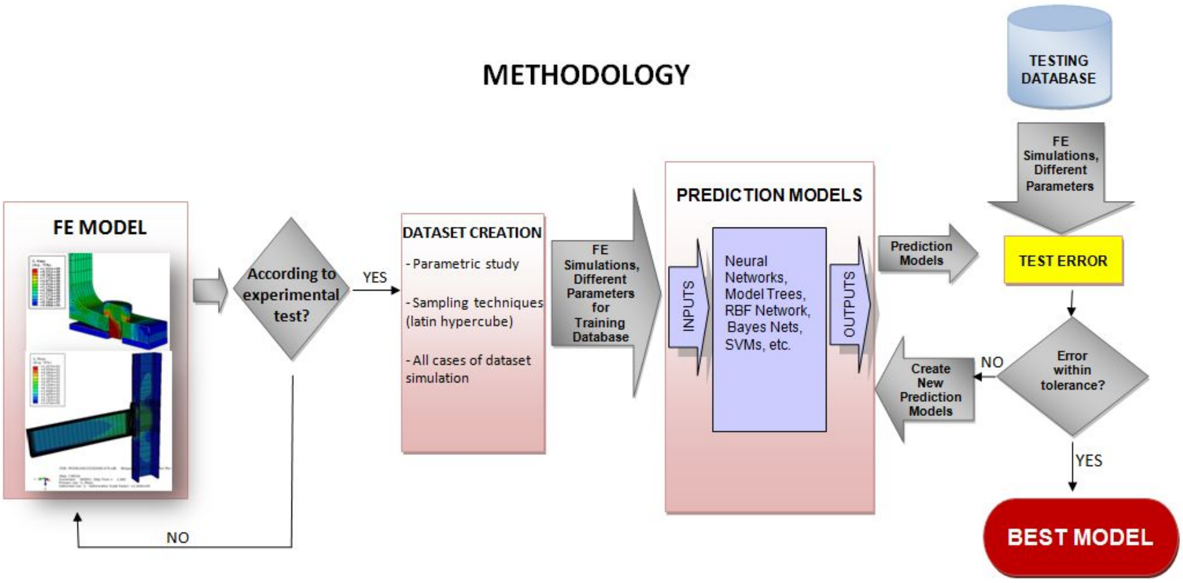
2.1. Finite Element Model

First of all, the FE model of the joint is created. The process is carried out by the commercial software ABAQUS©.

2.1.1. Type of Analysis

ABAQUS provides two types of analysis which are Standard and Explicit. Both of them follow different procedures. The former is based on the static equilibrium whereas in the Explicit analysis some increments (time t+Δt) are done and final states are based on displacements, velocities and accelerations (Vegte van der, and Makino, 2004).

Figure 1: Combining FEM, data mining and predictive models



In this study, the Explicit analysis is used because is the most suitable procedure due to the nonlinearities such as contacts and large deformations. Using this type of analysis is necessary to check that dynamic effects are negligible because these effects could cause wrong results. To avoid that, the relation between kinetic and internal energy of the joint should be below 5%.

2.1.2. Material Behaviour and Properties

Steel is represented by an elastic-plastic behaviour with strain hardening. Nominal stress-nominal strain curves do not present the actual elongation of the material when it is submitting to large deformations. This happen because these curves consider the initial dimensions of the test coupon, which are not constant. In ABAQUS, the nominal stress-nominal strain curves are replaced by the true stress-true strain (σ_t-ε_t) curve, which consider the variation of the dimensions during the test.

The expressions which relate the nominal and true values of stress and strain are shown in the following equations:

$$\sigma_n = \frac{F}{A_0} \tag{1}$$

$$\varepsilon_n = \frac{\Delta l}{l_0} \tag{2}$$

$$\sigma_t = \sigma_n(1 + \varepsilon_n) \tag{3}$$

$$\varepsilon_t = ln(1 + \varepsilon_n) \tag{4}$$

The failure will appear when the maximum Von Misses stress overcomes the true stress, which is given by the material behaviour response. The relation which expresses the failure condition is shown in the following expression:

$$\frac{\sigma_{eq}}{\sigma_{t\,máx}} \geq 1 \tag{5}$$

2.1.3. Boundary and Load Conditions

At the time of establishing the boundary conditions in the model, is necessary to take into account the symmetries with regard to the axes *x*, *y* and *z*. These will bring a substantial saving about the computational cost because it will not be necessary to simulate the whole model.

For Explicit analysis we use the “general contact” option to automatically set the contact features between all pairs of surfaces. This option allows the surfaces to slide when the limit value is achieved. Normal behavior that appears between two surfaces is defined by the tool “hard” contact. This tool generates a pressure when a pair of surfaces is in contact and it becomes zero when the surfaces are separated.

Tangential behavior is governed by the friction Coulomb’s law. With the option “penalty” it is possible to introduce this behaviour in ABAQUS. Depending on the treatment of the surfaces the value of the friction coefficient varies from 0.2 to 0.5.

2.1.4. Finite Element Meshing

The components of the joint are meshed with solid hexaedral elements. C3D8R is the name that receives the element used in ABAQUS and it is an 8-node linear brick with reduced integration.

To make the transition mesh, wedge elements are used in order to reduce the number of elements in those places where is not relevant to have a fine mesh. They are also used in irregular areas because wedge elements fit better than the hexaedral elements.

It is necessary to create a refined mesh in the areas which are close to the stress concentrations, for instance the area surrounding the bolt hole, in order to achieve accurate results.

2.2. Experimental Validation

The case studies should be validated against experimental tests carried out in the laboratory of the EDMANS group or taken out from a literature database. It is also advisable to iterate varying different parameters of the numerical model such as mesh, contacts or strain hardening of the material behavior. This process must be repeated until the model is calibrated with the tested joint.

2.3. Dataset Generation

In the generation of the dataset we have to take into account the range in which the input variables move in order to obtain accurate results. These results should be well distributed within all the possible combinations of parameters. To achieve that, it is necessary to use sampling techniques. In the input variables we consider geometrical parameters, contacts and the material behavior.

The Latin hypercube sampling (LHS) (McKay et al., 1979) is used to generate the dataset. With this technique the variance of the sample mean is less than a simple random sample. Finally, it is necessary to simulate all dataset cases in order to obtain the output variables that will be used to train and test predictive models.

2.4. Predictive Models

Once we reach the last step of the method, using the results of the all cases of dataset simulations it is possible to create predictive models. Different DM techniques such as artificial neural networks, regression trees, radial basis function networks or support vector regression model are trained in order to obtain the model which provides the minimum test errors. Among all types of models, we have to select the one that gives the results with the minimum error. There are two types of errors that will determine which prediction model is selected: root mean square error (RMSE) and mean absolute error (MAE).

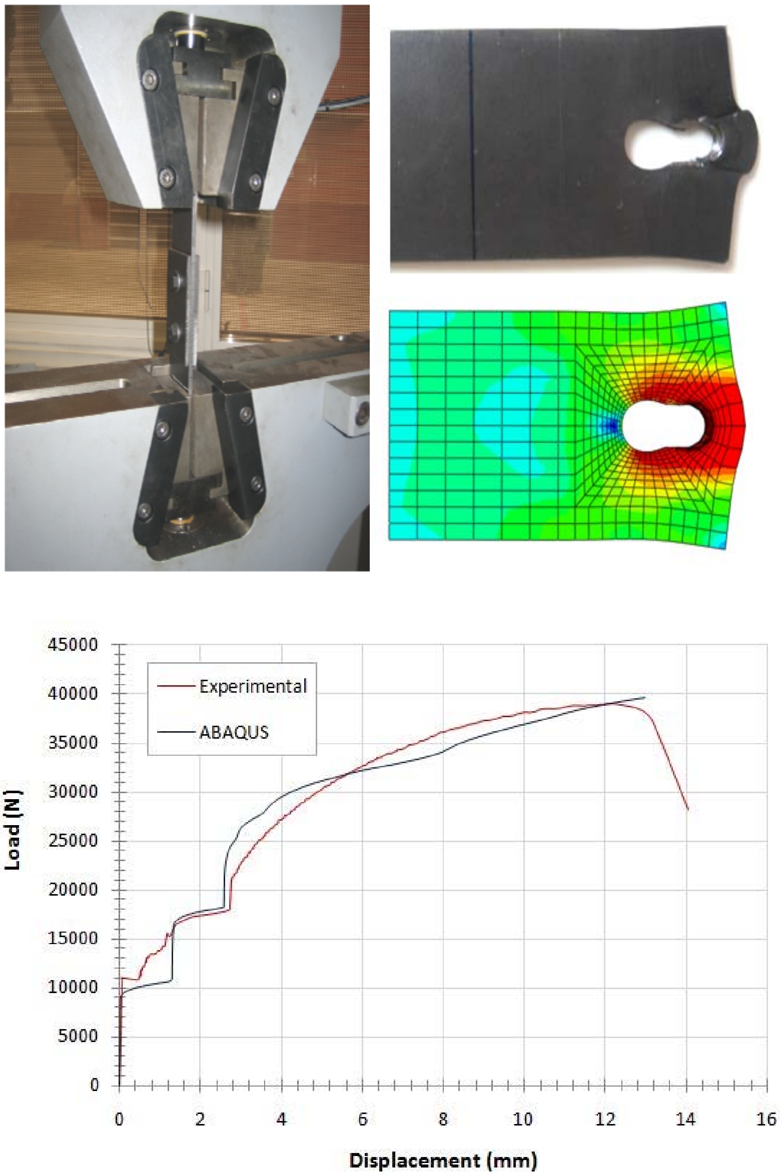
$$RMSE = \sqrt{\frac{1}{n}\sum_{k=1}^{n}\left(y(k) - \bar{y}(k)\right)^2} \tag{6}$$

$$MAE = \frac{1}{n}\sum_{k=1}^{n}\left|y(k) - \bar{y}(k)\right| \tag{7}$$

3. Cases of Study

The study of bolted connections through numerical models, experimental testing and data mining techniques has been one of the most relevant topics over several years in the EDMANS group. Three cases of the study are shown: lap joint, T-stub, and extended end-plate beam-to-column connection. The first two cases are completely made while the last one, which is more complex, is still on process.

Figure 2: Experimental validation of lap joint



3.1. Lap Joint

This type of joint is probably the simplest bolted connection. The characteristics of steel plates and bolts are shown in Table 1; following the rules for the steel S235 JR (EN 10025-2: 2004) and the quality of bolts (EC 3, 2005).

Table 1: Steel mechanical properties

	Steel grade	Minimum yield strength(MPa)	Tensile strength (MPa)	Minimum elongation (%)
Plates	S235 JR	235	360	26
Bolts	8.8	640	800	12
	10.9	900	1000	9

Numerical model has been calibrated against experimental tests that have been done in the laboratory (Fernández, et al., 2010). This can be seen in the Figure 2.

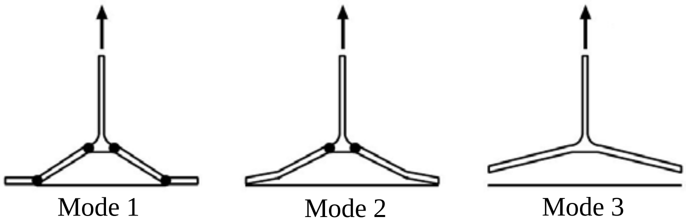
After calibrating the model, a parametric study was generated with some variations in the input parameters with the aim of creating the dataset (Fernández, et al., 2012). 1155 cases were carried out; with them was possible to make predictive models to assess the maximum force that can be supported by the joint.

After analyzing the errors that all type of prediction models has, we could conclude that one of the most suitable models in this case is a multilayer perceptron (MLP) artificial neural network (ANN).

3.2. T-stub Connection

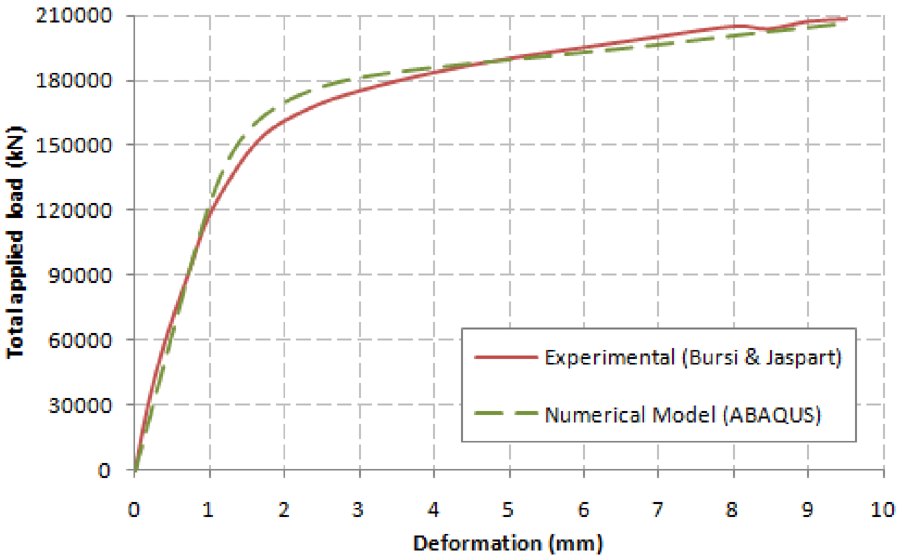
T-stub has also been studied by the EDMANS group. This type of joint is the basis where the component method was created. This type of joint may fail according to three failure modes (Figure 3). These failures depend on the hot rolled profiles and bolts geometry. The first one occurs when the ratio flange thickness/bolt diameter is low and four plastic hinges in the flange plates are located at the bolt holes and near the web plate. The second one is a combination between the development of two plastic hinges and the tension failure of the bolts. Finally, the third failure mode happens when tension failure of the bolts appears.

Figure 3: Types of failure in a T-stub connection



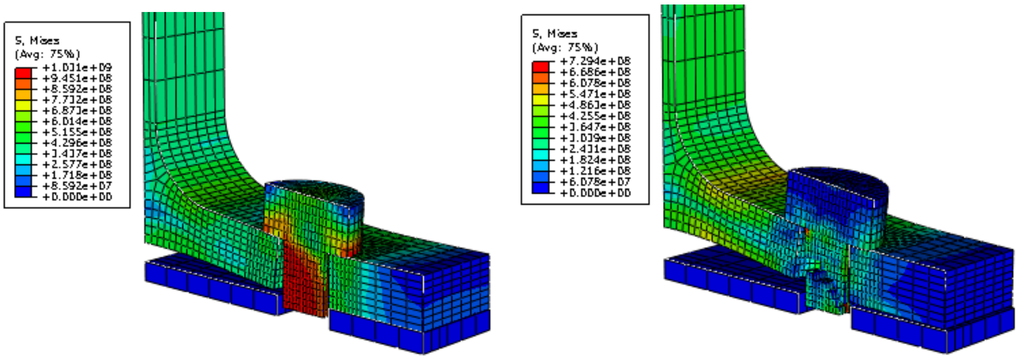
FE model is validated against an experimental test. (Bursi and Jaspart, 1997) (Figure 4).

Figure 4: Experimental validation of T-stub. (Fernández et al., 2011)



In Figure 5, von Misses stresses in the T-stub are shown. According to the experimental test, the failure occurred by bolt fracture after significant flange yielding (Fernández. et al., 2011). Two plastic hinges were developed in the bolt holes and near the web plate, according to the failure mode 2 (Figure 6).

Figure 5: Von Mises stress; a) maximum strength; b) axial failure in the bolt. (Fernández et al., 2011)

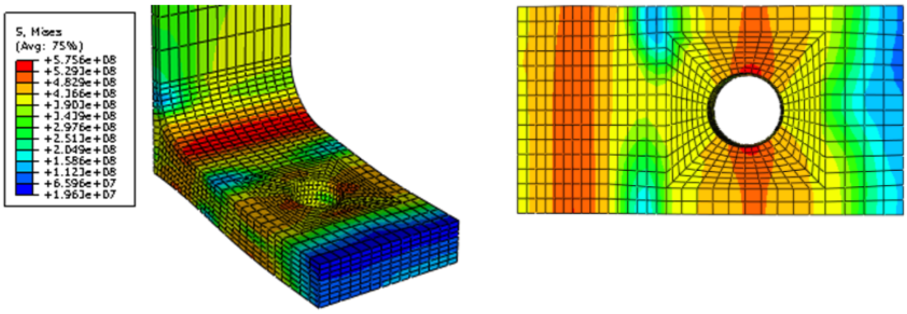


a) b)

Once that numerical model was validated against experimental test, a parametric study was carried out in order to study the influence of several geometrical parameters. The results obtained in the parametric study were used to build a useful database to train predictive models.

A predictive model was generated in order to obtain four output parameters. Several data mining techniques were trained with the aim of finding the best generalizing model of the problem. After studying the errors, we concluded that the correct technique to use is the multilayer perceptron artificial neural network (ANN), as in the lap joint's case. This technique was used in order to determine the initial stiffness of the joint, the elastic strength, the maximum strength and the maximum displacement.

Figure 6: Von Mises stress in the flange. (Fernández et al., 2011)



3.3. Extended End-plate Connection

Currently, EDMANS group is working on the development of a prediction model based on data mining techniques such as optimized bagging models.

Numerical model (Figure 7) has been generated and we have also obtained several experimental tests from a database (de Lima et al., 2004). Therefore, we have calibrated the numerical model, as it is shown in Figure 8.

Figure 7: Numerical model of extended end-plate connection

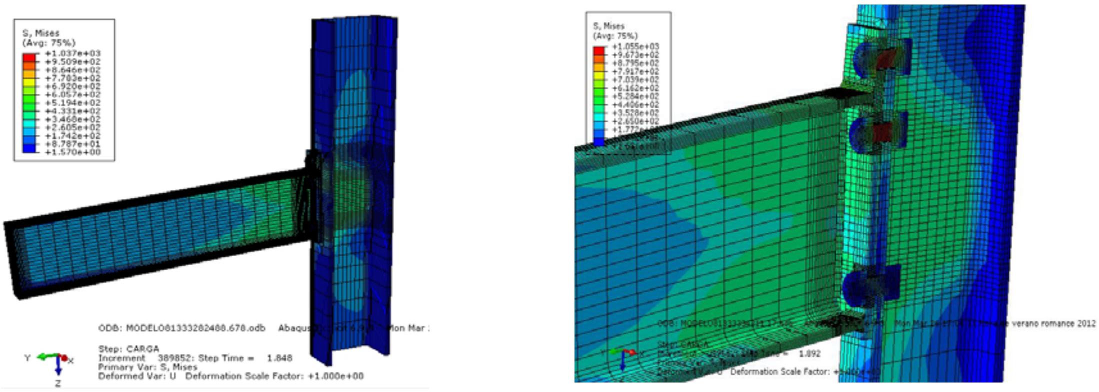
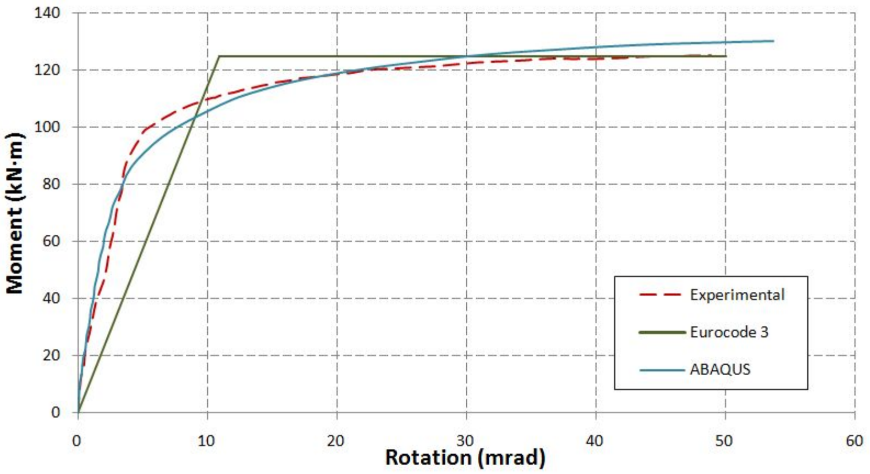


Figure 8: Experimental validation of beam-to-column extended end-plate connections



At the moment, a parametric model is being developed with the aim of applying Data Mining (DM) techniques which simplify the numerical models and reduce the computational cost.

4. Conclusions

Bolted connections represent complex elements of the utmost importance in structural design and they should be carefully assessed. Even though the reliability of the component method adopted by the Eurocode 3, more sophisticated methods are needed to deal with the nonlinearities involved in the calculation process and also for assuring the ductility capacity of connections. To this end, numerical models provide accurate results in the characterization of the bolted connections response. These models are able to reproduce the nonlinearities that exist on the design of these structural elements. In spite of it, the work becomes more complex when is necessary to carry out repetitive tasks with parameter variations, appearing disadvantages because of its excessive computational time.

In this paper, a methodology based on the combination of numerical models and data mining techniques has been presented in order to reduce the computational cost associated to the FE simulations and so as to avoid the preprocessor and postprocessor tasks. For this purpose, the creation of a training dataset from a limited number of FE simulations provides useful information needed to train a predictive model. Finally, the predictive model represents a simplified tool that can replace the expensive FE model without significant loss of accuracy.

The proposed methodology has been successfully applied in both the lap joint and the T-stub connection. Moreover, in order to it is expected to develop a similar tool which can be applied in more complex configurations such as the extended end-plate.

Finally, we consider that the development of these predictive models for the calculation of bolted connections represents an important advance not only in the research field but also from the practical point of view. Several advantages characterize the developed tool: on the one hand enables the structural designer to make accurate predictions of the connection response without significant computational cost. Therefore, the predictive model can be used in an optimization process in order to search the geometric and mechanical input parameters which minimize an objective function, such as cost or weight. On the other hand, this tool could be easily integrated in steel structures software so as to include a refined model for the bolted connections design.

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