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Rotational behaviour of column base plate connections: Experimental analysis and modelling

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ABSTRACT

A research program aimed at the development of a mechanical model to predict the rotational behaviour of base plate connections under cyclic loads has been recently undertaken at Salerno University. The evaluation of the accuracy of the component approach for predicting the rotational behaviour of base plate connections up to failure under monotonic loads has been carried out as first step of the planned research activity. The accuracy in predicting the rotational stiffness, the flexural resistance and the overall moment–rotation curve of base plate connections by the component method given in Eurocode 3 is evaluated with reference to the experimental tests recently carried out at Salerno University. In particular, the specimens have been preliminarily tested in elastic range under different values of the column axial load and, successively, loaded up to collapse.

Such experimental tests are presented and discussed in this paper. In order to widen the investigated range of the geometrical and mechanical parameters affecting the behaviour of base plate connections, the comparison between the predictions coming from component method and experimental tests has been extended not only to the authors' own tests, but also to a significant number of tests collected from the technical literature.

1. Introduction

In last years, following the introduction in Eurocode 3 [5] of detailed procedures for predicting the joint rotational behaviour, the attention of researchers towards advanced modelling of steel framed structures has gradually increased. In particular, with reference to seismic design issues, more and more interest has been devoted to the study of the cyclic rotational behaviour of steel members and connections with the aim to develop reliable models to be successfully used in the non-linear analysis of steel framed structures subjected to earthquakes [2,18,15,19–21]. In addition, significant research activity has been also carried out aiming to the improvement of structural models for non-linear dynamic analyses by reducing the epistemic uncertainties due to the prediction of the cyclic behaviour of dissipative zones [19,20,8].

It is well known that accurate seismic non-linear analyses require an appropriate modelling of the hysteretic cyclic behaviour of steel members and connections. These models must be able to grasp with satisfactory accuracy the main phenomena characterising the cyclic response under seismic actions, such as strength and stiffness degradation and pinching phenomena.

Regarding connections, the modelling of the rotational behaviour under monotonic loading conditions has been extensively studied both with reference to beam-to-column connections and with reference to column–base connections leading to the development of the so-called component method codified in Eurocode 3. The main advantage of the component method is its ability to allow the prediction of the rotational behaviour of different joint typologies by means of a unified approach, starting from an appropriate identification and modelling of all the sources of strength and deformability, i.e. all the components. Even though the method has been codified dealing mainly with the prediction of the stiffness and strength of the components starting from the values of their geometrical and mechanical properties, the possibility of predicting also the component ductility has been recently pointed out [25,12]. Therefore, it can be stated that the modelling of the whole moment–rotation curve up to collapse can also be obtained, provided that rules for predicting the ultimate deformation of the joint components are available, at least with reference to the weakest joint component which governs the plastic rotation capacity of connections.

Regarding the prediction of the cyclic behaviour, additional studies and experimental tests are still needed in order to develop

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accurate and reliable models. In particular, with reference to beam-to-column connections, some works have been recently developed aiming to the extension of the component method to the prediction of the cyclic behaviour [23,19,20]. These studies have shown that a reliable modelling of the cyclic behaviour of connections, accounting for strength and stiffness degradation and pinching effects, is possible, provided that an accurate modelling of the extensional (force versus displacement) behaviour of each joint component is available.

It is evident that an accurate modelling of steel frames subjected to seismic actions requires not only a reliable modelling of the cyclic behaviour of beam-to-column connections, but also an accurate modelling of the cyclic behaviour of column–base connections. Unfortunately, with reference to the cyclic behaviour of column base plate connections, predicting models based on the component approach are nowadays not available in the technical literature. Therefore, within this framework, the main purpose of the research activity planned at Salerno University is the investigation and modelling of the cyclic behaviour of the base plate connections. In particular, the whole research program on this topic requires the development of the following steps:

- *Step 1:* Theoretical and experimental study of the monotonic ultimate behaviour of base plate connections aiming to the evaluation of the degree of accuracy of Eurocode 3 approach for predicting the rotational stiffness and the flexural strength of column–base plate connections.
- *Step 2:* Development of a method for predicting the plastic rotation capacity of base plate connections starting from the knowledge of the ultimate deformation of components [22].
- *Step 3:* Definition of new criteria for designing full-strength base plate connections with adequate overstrength to account for material strain hardening and uncertainties deriving from random material variability of the connected column.
- *Step 4:* Modelling of the cyclic behaviour of base plate connections by the component approach and definition of practical rules for designing dissipative column base plate connections.

In this paper, the results gained during the first step of the planned research activity are presented and discussed. In particular, the accuracy of the component method suggested by Eurocode 3 for predicting the rotational stiffness and flexural strength of column–base connections is analysed starting from the experimental test results of Salerno University and successively with reference to those coming from a wide collection of tests available in the literature. Even though in the present work reference is made to the European practice, it is important to underline that the new experimental results herein presented can be also useful for further investigations dealing with the accuracy of alternative analytical models proposed in technical literature which are however out of the scope of this work.

2. Prediction of the moment–rotation curve

The prediction of the rotational behaviour of base plate joint is even more complex than that of beam-to-column connections due to several factors, such as the bond between the anchor bars and the concrete base material, the behaviour of the bedding grout and the complex evaluation of the stiffness and resistance of the concrete below the compressed flange, due to the contact phenomena and the resulting stress distribution between the base plate and the concrete. Moreover, the rotational response is controlled by interactions between these components. Previous research has sought to characterise these interactions and their effects on key aspects of connection rotational response. Experimental studies [6,29,3,1] have led to the development of methods for calculating the flexural strength of these connections [7,13,9].

In addition, also the loading process plays an important role in the behaviour of base plate joints. In the technical literature, two different types of loading process are usually adopted: the first one is characterised by a proportional loading process where the vertical load and the bending moment are proportionally increased, so that the eccentricity is constant during the loading process; conversely, the second one is characterised by a load process where the vertical load is applied in a first loading phase and, subsequently, the application of an increasing bending moment is carried out up to failure. In this case, the eccentricity is continuously increasing giving rise to an additional non-linearity source in the connection behaviour.

The application of the component method requires the development of three steps:

- Identification of the deformability and strength of components.
- Mechanical characterisation of each component.
- Assembly of the mechanical model of the whole connection.

Several studies have been also carried out to develop procedures to represent interactions between the various components and for evaluating the rotational stiffness of column–base connections [30,31,16,27,6,17].

With reference to the procedure proposed by Eurocode 3, the sources of deformability and resistance for a usual base plate joint of "exposed" typology are: the concrete in compression, the base plate in bending, the anchor bars in tension and the column flange and web in compression. This latter component is involved only in the resistance evaluation and does not provide a contribution to the connection deformability.

In case of column–base connections subjected to centred axial load, Eurocode 3 suggests to consider three compressed T-stubs located according to the column flanges and web (Fig. 1a). Conversely, in case of column–base connections subjected to axial load and bending moment, a simplified approach is proposed by neglecting the contribution due to the web T-stub. Starting from the translational and rotational equilibrium conditions, the connection flexural resistance $M_{j,Rd}$ can be expressed as a function of the load eccentricity e as follows:

$$\text{low eccentricity } e < z_{c,r} \qquad M_{j,Rd} = \min\left\{\frac{F_{cl,Rd}z}{z_{c,r}/e - 1};\quad \frac{F_{cr,Rd}z}{z_{c,l}/e + 1}\right\} \tag{1}$$

$$\text{high eccentricity } e > z_{c,r} \qquad M_{j,Rd} = \min\left\{\frac{F_{tl,Rd}z}{1 - z_{c,r}/e};\quad \frac{F_{cr,Rd}z}{z_{t,l}/e + 1}\right\} \tag{2}$$

where $F_{cl,Rd}$ is the resistance in compression of the left T-stub, $F_{cr,Rd}$ is the resistance in compression of the right T-stub, $F_{tl,Rd}$ is the resistance in tension of the left T-stub, z_{cl}, z_{cr}, z_{tl} are the distances from the column axis of the components depicted in Fig. 2 and z is the lever arm equal to $z_{cl} + z_{cr}$, in case of small eccentricity, and equal to $z_{tl} + z_{cr}$, in case of high eccentricity.

The resistance of the base plate in tension $F_{tl,Rd}$ can be modelled by means of an equivalent T-stub according to the well-known Eurocode 3 formulations. In particular, in case of base plates allowing the development of prying forces, it corresponds to the minimum value of the resistances corresponding to type 1, 2 and 3 collapse mechanisms; conversely, when the base plate is not stiff enough, it is equal to the minimum resistance given by type 1* and 3 collapse mechanisms. Therefore, the resistance of the base plate in tension can be evaluated by means of the following relationships: