MODELLING OF STEEL–TO–CONCRETE END–PLATE CONNECTIONS UNDER MONOTONIC AND CYCLIC LOADING

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Abstract

In this paper a model is introduced for the analysis of end-plate type steel-to-concrete connections under monotonic and cyclic loading. The developed model predicts the global response of the connection from the local behaviour of the 'tension' and 'compression' zones. The load-deformation relationships of the zones are analysed independently by two non-linear 2D FEM models. The calculated monotonic moment–rotation curves are presented and compared to the experimental results. The application of the model for cyclic analysis is also demonstrated. It is concluded that the relatively simple model provides good prediction for the behaviour of mixed connections under general loading conditions.

Keywords: steel-to-concrete connection, moment–rotation characteristic, cyclic behaviour, zone model.

1. Introduction

Steel-to-concrete connections are connecting steel, concrete, reinforced concrete and composite structural elements. End-plate type mixed connections are typically used in steel beam-to-reinforced concrete or composite column joints (WAKABAYASHI, 1994), steel or composite column bases (LESCOUARCH and COLSON, 1992), and in beam-to-beam joints of composite bridges (OHTANI et al., 1994). The behaviour of these connections under general loading conditions is a very complex phenomenon.

Formulas for full strength design of mixed connections are derived assuming reinforced concrete cross-section and equivalent rigid plate approach. A summary of these design methods for steel column bases can

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be found in WALD, 1993 and adopted in Eurocode 3, 1991, too. Although the applied hypotheses are not correct in general (PENSERINI and COLSON, 1989), the methods provide acceptable prediction for the ultimate strength in the design practice. Connections that are designed in this way are considered as 'rigid'. However, from the available test results it can be seen that the nominally fixed mixed connections exhibit semi-rigid nature, the rotational stiffness depends on the axial force, and its deterioration is significant under cyclic loading (AKIYAMA, 1985 PENSERINI, 1991 ASTANEH et al., 1992 WALD, 1993 DUNAI et al., 1994). Recent extended experimental and theoretical research studies are focusing on these aspects of structural behaviour. Different levels of models are developed to analyse the phenomena and to predict the moment–rotation ($M - \Theta$) relationship (PENSERINI, 1991 MELCHERS, 1992 FLÉJOU, 1993 WALD, 1993 SOKOL et al., 1994, IVÁNYI and BALOGH, 1994).

In the current research a fundamental experimental program is completed on the rigidity of general steel-to-concrete end-plate connections. Specimens with typical structural arrangements are designed mostly to exhibit the phenomena rather than to represent practical connections. On the basis of experimental findings a prediction model is developed for the monotonic and cyclic moment-rotation behaviour. The developed model is an extended component model which predicts the moment–rotation response from the independent local behaviour of the 'tension' and 'compression' zones of the connection. The load–deformation relationships of the zones are analysed separately by non-linear 2D FEM models. The cyclic model is developed on the assumption of so-called zero-oriented behaviour as it is defined in Section 3. The monotonic $M - \Theta$ curves are compared to the results of the experimental study (DUNAI et al., 1994). The cyclic $M - \Theta$ curves are presented and analysed by the cyclic characteristics (ECCS, 1986).

2. Experimental Program

In the experimental program three test specimens are designed to demonstrate the typical structural arrangements and behavioural aspects of end-plate type mixed connections. The details of the specimens can be seen in *Fig. 1*.

Specimens SP-1 and SP-2 are designed as partial strength connections, while SP-3 as a full strength connection. The symmetrical steel-concrete-steel connection detail is placed in the center of a steel beam. The steel beam, containing the mixed connection is loaded by monotonic and cyclic bending moment in a four-point-bending arrangement in a combination of constant axial compressive force. The end-plate deformation of

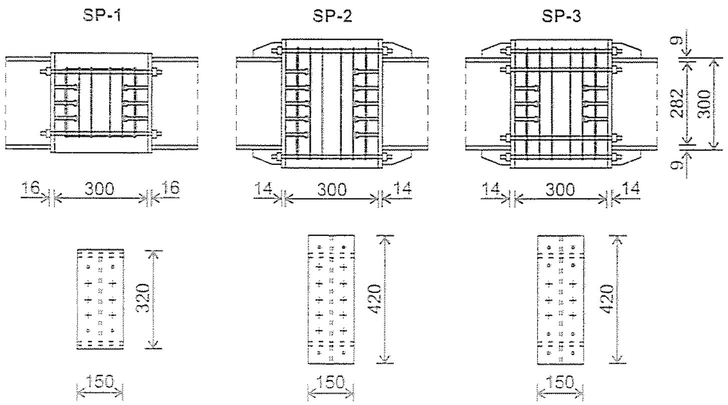

Fig. 1. Test specimens

the connection is measured by relative displacement measurement devices between the pertinent edge points of the two end-plates, as illustrated in *Fig. 2*. Further details of the experimental study can be found in (DUNAI et al., 1994).

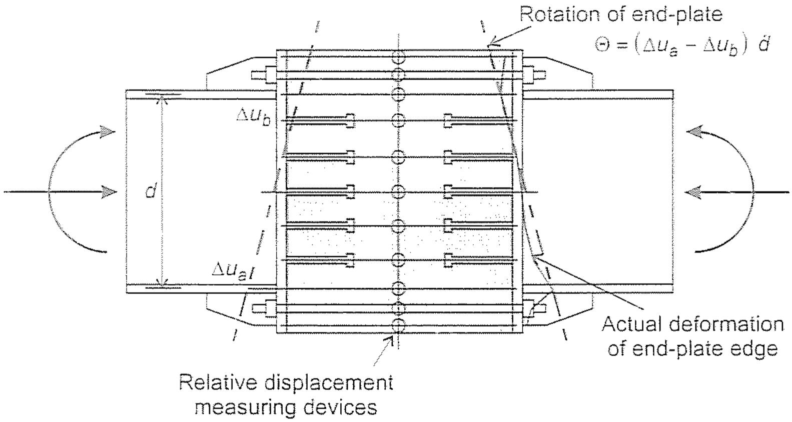

Fig. 2. Measuring and interpretation of rotation

The measured positive and negative envelopes of moment-rotation and moment-relative displacement relationships of specimen SP-1 for a given constant axial force are illustrated in *Figs. 3 (a), (b)* and *(c)*, respectively. These results demonstrate the behaviour of the tension and compression zones and their influence in the global response. On the basis of these experiences a model is introduced for the monotonic and cyclic analysis of mixed connections.

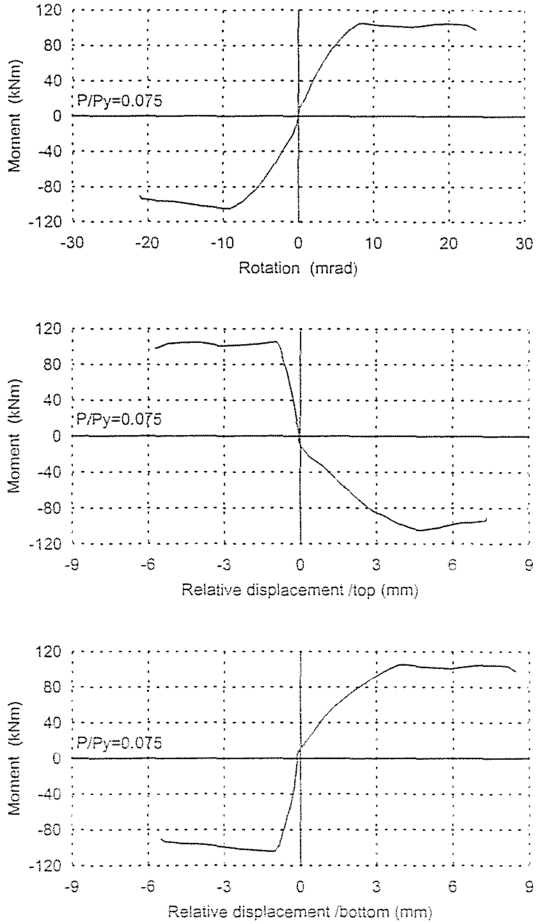

Fig. 3. Moment – rotation and moment – relative displacement curves of SP-1

3. The Zone Model

3.1. General

The behaviour of a nominally fixed steel-to-concrete connection is highly influenced by the rigidity of its end-plate, as it is shown in ASTANEH et al., (1992). From this point of view three types of behaviour can be defined (*Fig. 4*).

In case of thick (i.e. rigid) end-plate the equivalent reinforced concrete model is a simple and accurate way for the analysis of mixed connections.

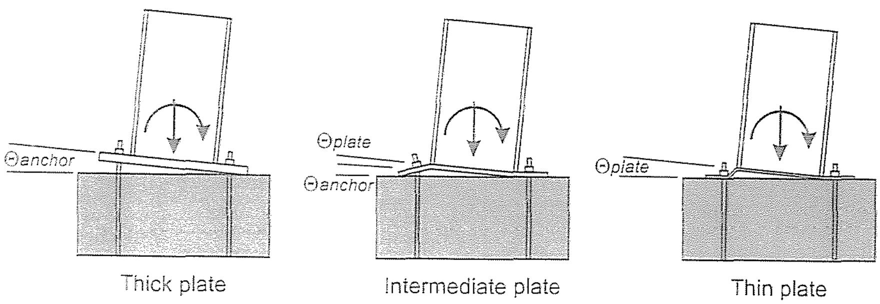

Fig. 4. Classification of mixed connections (ASTANEH et al., 1992)

This model, however, is not correct if the end-plate is flexible, since the dominant plate bending is eliminated.

In case of thin (i.e. flexible) end-plate the local plate bending is significant under the flanges. The global connection behaviour can be derived from the tension and compression zones' behaviour. In case of intermediate end-plate the two types of behaviour are combined, the analysis of which requires a more refined and more complicated model (e.g. 3D finite element model).

In this Section a model is described which can be a simple solution for the analysis of mixed connections with flexible end-plates. The model is based on the experimental observation that, as it has been already mentioned, in case of thin end-plate the deformations are concentrated under the flanges, while the middle part of the connection remains practically undeformed. This is demonstrated in *Fig. 5* where the end-plate deformation of SP-1 is plotted.

3.2. Assumptions

The zone model is applicable for nominally fixed steel-to-concrete end-plate connections, under combined axial force and bending moment loading. Shear force, however, is not taken into consideration. The model, using the idea of so-called component models, predicts the global behaviour of the connection from the local behaviour of its components. The basic assumption of the model is as follows: two components are defined, compression and tension zones, and the two zones are analysed separately. In other words it is assumed that there is no interaction between the tension and compression zone of the connection. According to the above-mentioned as-

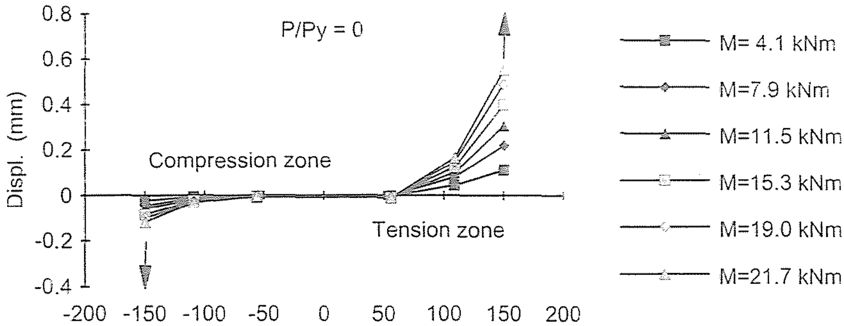

Fig. 5. End-plate deformation of SP-1

sumption the global response of the connection can be determined in two steps, as it is illustrated in *Fig. 6.* These two steps are described in the following Sections.

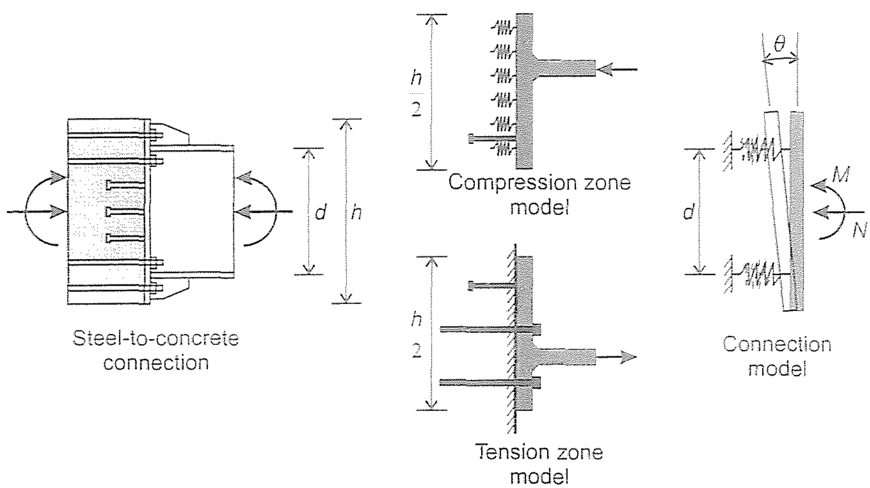

Fig. 6. Derivation of zone model

It has to be emphasized that the applicability of the zone model must be limited. In Section 4 some typical practical cases are presented where the model is verified by the test results. Nevertheless, a parametric study would be necessary to find the limits of the model.

3.3. Analysis of Tension and Compression Zones

First the behaviour of the two zones is analysed. The zone behaviour is characterized by the flange force – displacement ($P-u$) relationship which is established by FEM analysis. The main features of the applied finite element models are the following:

- the 3D geometry is transformed to a 2D plane stress model (DUNAI, 1992);
- the concrete support is assumed to be rigid in the tension zone model, while in the compression zone model it is modelled by a non-linear Winkler-type foundation, using an equivalent elastic modulus;
- the constitutive model of both steel components and concrete foundation is a multi-surface Mroz model (MOSADDAD and POWELL, 1982);
- the separation–recontact phenomena are taken into consideration between the bolt head and the end-plate as well as between the end-plate and concrete foundation;
- for the length of the anchor bolts an effective length is used.

3.4. Determination of $M-\Theta$ Characteristic

If the flange force – displacement relationship of both zones is known, the relative rotation of the connection can easily be calculated in three steps:

- calculation of (P) flange forces from the given (bending moment+axial force) loading by using equilibrium equations;
- determination of corresponding relative displacement from the $P-u$ relationships of the zones;
- calculation of relative rotation from the displacements of the two zones. Repeating these three steps, arbitrary point of $M-\Theta$ curve can be determined.

3.5. Considerations for Cyclic Loading

The model can be extended also to cyclic loading. The basic assumptions remain unchanged, as well as the procedure of determination of $M-\Theta$ characteristic is the same. Using a step-by-step procedure, the whole cyclic curve can be determined. The only difference is in the $P-u$ relationship of the zones where the effect of unloading is taken into consideration by introducing a further assumption, on the basis of experimental results. In each step when flange force begins to decrease in a given zone, the $P-u$ relationship is modified. To do this the monotonic $P-u$ curve is used as a

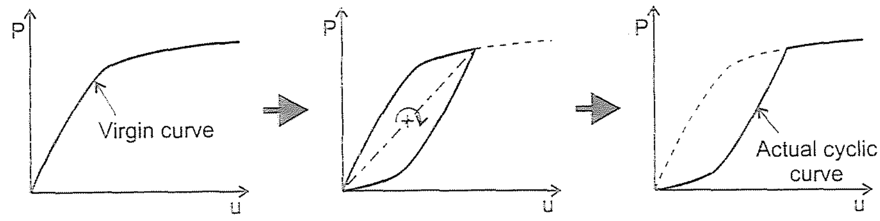

Fig. 7. Derivation of cyclic $P - u$ curve

virgin curve. The determination of cyclic flange force – displacement curve is demonstrated in *Fig. 7*.

It has to be noted that this modification procedure is mainly based on practical considerations. For using this assumption, $M - \Theta$ curves can be obtained that are similar to those obtained by tests, without losing the efficiency of the model. Nevertheless, this simplification has two important consequences. These are:

- no residual deformation remains after unloading (zero-oriented cyclic behaviour);
- reloading takes place along the previous unloading path, which means that no hysteresis loop is formed during unloading–reloading.

4. Numerical Studies

4.1. General

In this Section the results of comparative studies are presented. The model described in Section 3 is applied for the analysis of three steel-to-concrete joints under monotonic and cyclic loading. These joints are identical with those of specimens SP–1, SP–2 and SP–3 of the experimental program presented in Section 2. For the sake of simplest comparison also the loads acting on the connections are in accordance with the tests.

4.2. Flange Force – Displacement Characteristics

As the first step of calculations, the zone behaviour is analysed under tensile and compressive flange force. The flange force – displacement curves are obtained by the finite element analysis the main features of which are

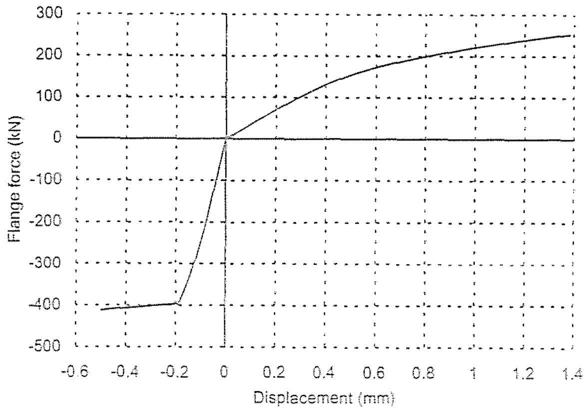

Fig. 8 Calculated flange force – displacement relationship of SP-2

described in Section 3.2. As an example, the calculated $P-u$ relationship of SP–2 is plotted in *Fig. 8*.

4.3. *Monotonic Behaviour*

According to the experimental study, the three specimens are analysed under combined constant axial compressive force ($P = 103.5$ kN) and bending moment. (The value of the axial force is chosen so that the P/P_y ratio would be equal to 0.075, P_y being the normal resistance of the steel section which can be calculated as the product of the cross-sectional area and the yield strength of the steel material.) In *Fig. 9* the calculated moment–rotation curves are presented together with those obtained from tests, for SP-1, SP-2 and SP-3, respectively.

By inspection of the diagrams it can be seen that the calculated and experimental curves very well coincide with each other in their initial part, which means that the zone model gives very good prediction for the initial stiffness of the analysed connections. On the other hand, the moment capacity is underestimated. This underestimation can be traced back to the simplicity of the model, namely: neither the 2D behaviour of the end-plate and concrete foundation, nor the interaction between the tension and compression zone is taken into consideration.

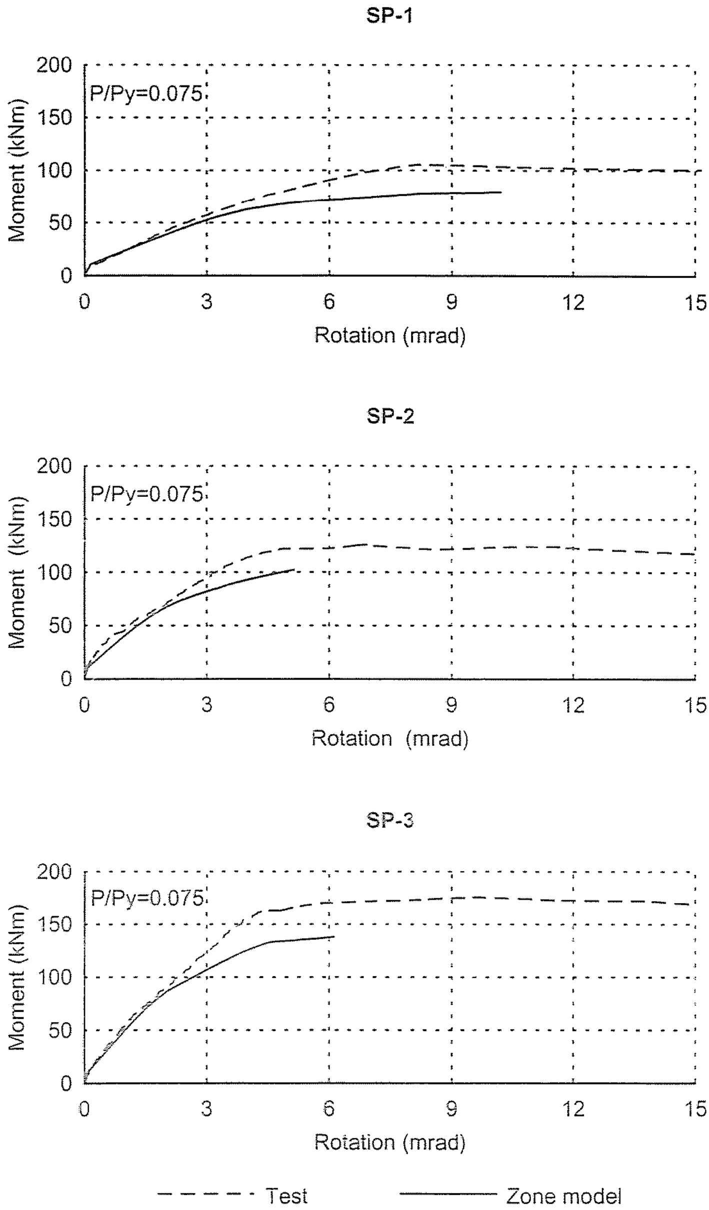

Fig. 9. Experimental and calculated moment–rotation curves

4.4. Cyclic Behaviour

A study is completed to analyse also the cyclic behaviour of the specimens. *Figs. 10* and *11* show the experimental and calculated moment–rotation curves of SP-1 under cyclic loading, respectively. In order to characterize these curves numerically, four nondimensional quantities are calculated to each hemicycle, according to the ECCS recommendations (ECCS, 1986). These are: resistance ratio (ε), rigidity ratio (ξ), full ductility ratio (μ) and absorbed energy ratio (η). These ratios can be calculated by the following formulae, using the notations of *Fig. 12*:

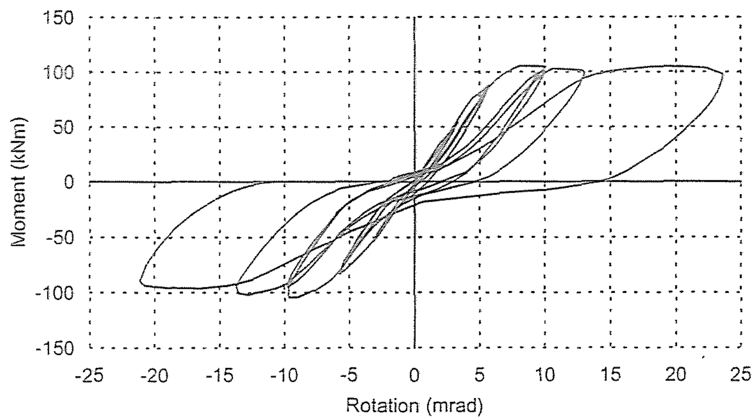

Fig. 10. Experimental cyclic moment–rotation curve of SP-1

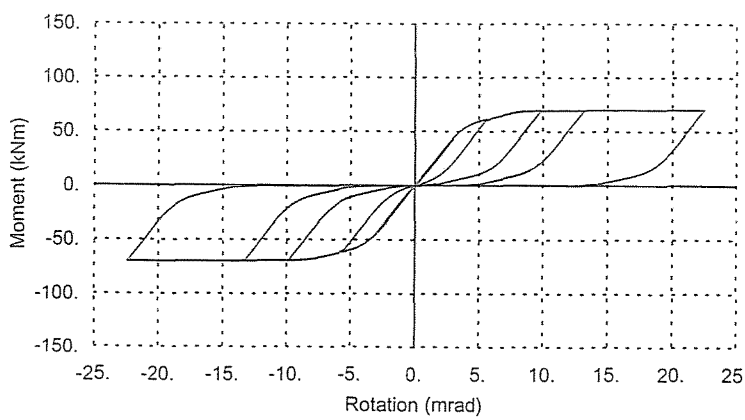

Fig. 11. Calculated cyclic moment–rotation curve of SP-1

The above-mentioned four characterizing parameters are presented in *Fig. 13* in function of the partial ductility, for positive hemicycles of both

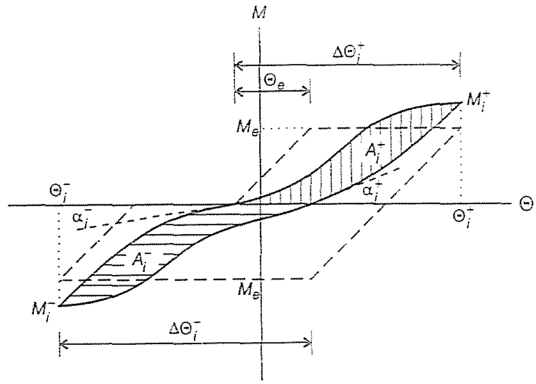

Fig. 12. Interpretation of the characterizing parameters of cyclic curves

experimental and calculated curves of SP-1. Partial ductility can be calculated as:

$$\mu_{oi}^{+} = \Theta_i^{+}/\Theta_e.$$

As far as the full ductility ratio is concerned the coincidence between the experimental and calculated curves is excellent. In case of the three other ratios differences can appear, their tendencies, however, are similar. The resistance ratio highly depends on the elastic moment resistance (M_e) of the connection. If the experimental and the calculated elastic moment resistances differ from one another, the resistance ratios will differ, too. In case of the rigidity ratio a decreasing tendency can be observed, the model, however, overestimates the degradation of connection rigidity. This overestimation is caused by the simplifying assumptions of the model. Unlike the rigidity degradation, the absorbed energy ratio is underestimated, which can be derived mainly from the assumption of unloading.

5. Conclusion

In this paper the so-called zone model is introduced for the analysis of nominally fixed steel-to-concrete end-plate connections. Numerical studies are completed to compare the model's results to those of tests, under monotonic and cyclic combined loading. The main conclusions of the current research can be drawn as follows:

- The zone model keeps the simplicity of the classical component models, while takes the most significant interaction phenomena into consideration.
- Using an experimental assumption, the model can be extended for cyclic analysis.

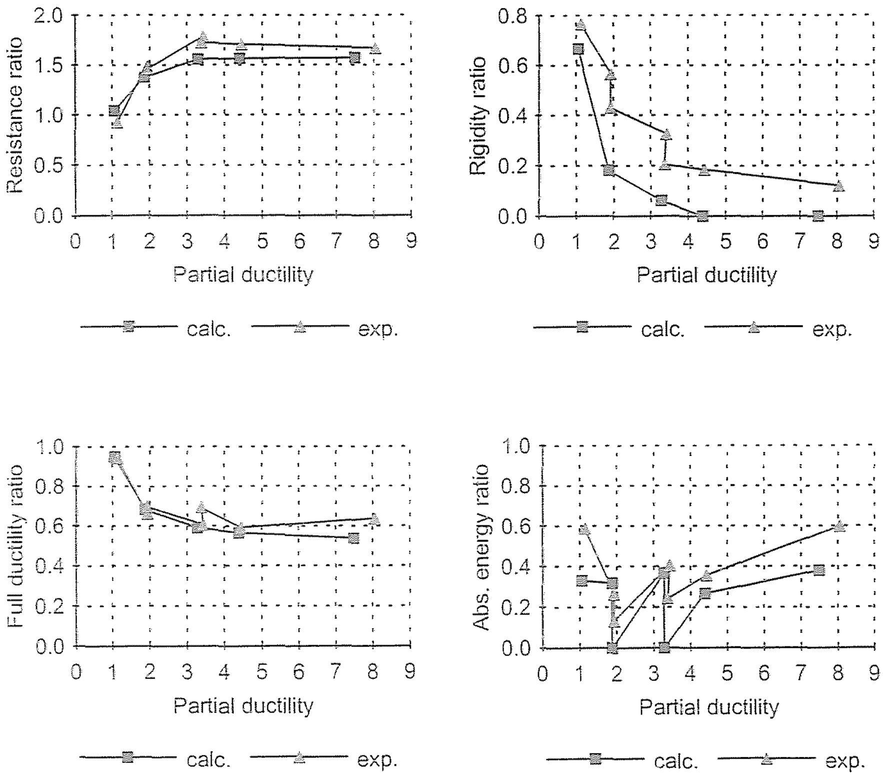

Fig. 13. Characterizing parameters of the moment–rotation curves of SP-1

- According to the numerical studies, the zone model very well describes the initial behaviour of the analysed connections, while slightly underestimates their moment capacity.
- In case of cyclic loads the model gives good prediction for the tendencies of cyclic behaviour.

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