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PREDICTION OF THE CYCLIC BEHAVIOR OF MOMENT RESISTANT BEAM-TO-COLUMN JOINTS OF COMPOSITE STRUCTURAL ELEMENTS

Nauzika Kovács*, László Dunai* Luís Calado**

* Budapest University of Technology and Economics, Department of Structural Engineering, Hungary
e-mails: nauzika@vbt.bme.hu, ldunai@epito.bme.hu

** DECivil – Civil Engineering Department, IST Instituto Superior Técnico, Lisbon, Portugal
e-mail: calado@civil.ist.utl.pt

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Abstract. *An experimental program is performed on end-plate type joints (with different end-plates and bolts) of composite structural elements under cyclic loading. In parallel a numerical method is developed to predict the experimental cyclic behavior modes of the joints. The method is based on the monotonic joint behavior, assuming the knowledge of the typical hysteretic cycles. The method is applied in combination with verified finite element models to complete a parametric study. In this study the effect of the end-plate thickness and bolt size on the cyclic behavior is investigated. Finite element analyses are used to determine the monotonic force-displacement relationships. On this base the hysteretic behavior is derived by the developed prediction model, cycle by cycle, applying the ECCS recommendations for the cyclic loading history with the aim to evaluate the absorbed energy in order to determine the structural efficiency of the joints.*

1 INTRODUCTION

The focus of this research is on the beam-to-column connection zone of the dissipative structures, which are applied in seismic regions due to their ductile behavior and high strength. The seismic energy of the earthquake is absorbed by the plastic deformation in the joints and in the connecting elements. The current research studies this ductile plastic hysteretic force-displacement response of the end-pate type joints of the moment resisting frames by experimental tests and analytical investigations.

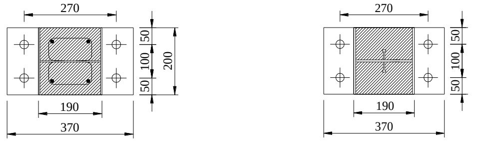
The end-plate type joints are widely used due to their simple production and erection procedure, however, the application of these joints, requires sophisticated design method due to their semi-rigid nature. Standard design method exists for the determination of the joint static behavior defining the moment resistance, initial stiffness and rotational capacity, but not considering the cyclic loading and the seismic response of the joints. The purpose of the current research is to complete analytical parametric studies on end-plate type joints of concrete in-filled composite members reflecting on the seismic behavior as the energy absorption capacity during the consecutive cycles. In the presented work the aim is to develop a method, which predicts the absorbed energy of the studied joint. First the monotonic joint model is developed by FE model and verified by experimental results as the base of the proposed semi-empirical method. By the combination of the finite element analysis and the developed cyclic prediction method, using the experimentally determined typical hysteretic diagrams, the experimental results are extended. The focus of the current research is on analyses of the bolt-failure and the end-plate type failure the studied joints. A parametric study is performed not exceeding the experimental global joint geometry with the aim to determine the absorbed energy capacity and to conclude the favorable end-plate and bolt geometry from seismic point of view.

2 EXPERIMENTAL PROGRAM

An experimental research program was carried out on 12 end-plate type bolted joints of concrete filled I-sections to investigate their response under cyclic bending. The test program was carried out as a cooperative effort between the Budapest University of Technology and Economics and the Technical University of Lisbon, where all the tests were conducted. In this systematic test program, the first six specimens were used to study basic behavior modes of the bolted end-plate type joints of composite members. Following these tests, six similar joints of composite members with slender cross-section were tested to study the beam interacting zone. The details of the experimental programs are presented in [1], here only short summary is given.

2.1 Test arrangement

The test arrangement is a cantilever type one, the specimens are subjected to cyclic loading, according to the ECCS standard-based loading history [2], in altering directions. The specimens are designed with H-shaped composite element (hot-rolled or welded) with concrete filling and reinforcement or headed studs between the flanges, as shown in figures 1a) and b).

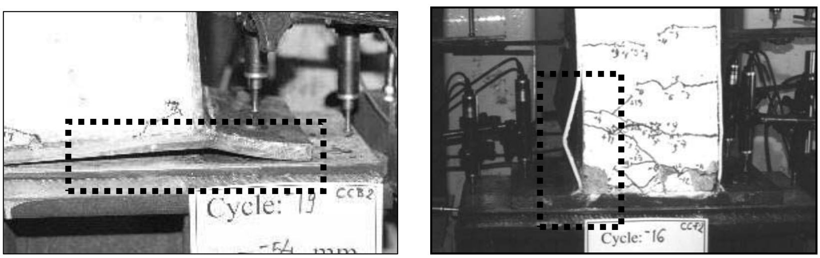


a) with reinforcement b) with headed studs

Figure 1: Composite specimens.

2.2 Test results

Two types of behavior are observed during the tests. When the resistance of the connecting members (beam) is relatively higher, the failure is occurred in the connection with residual plastic deformation and crack propagation of the end-plates and bolts, as shown in figure 2a). In case of stronger connecting elements (bolts, end-plate), the cyclic behavior is governed by the local plate buckling of the member interacting zone, as shown in figure 2b).



a) connecting element type b) local buckling type

Figure 2: Experimental behavior.

On the basis of the measured data the cyclic moment-rotation curves are determined. From the cyclic moment-rotation relationship the cyclic parameters (ductility, rigidity/resistance degradation and absorbed energy) are also evaluated. The cyclic behavior modes of the studied connection are classified by the governing phenomena: the bolt yielding and fracturing in tension (bolt-failure); the plate deforming in bending (plate-failure); the interaction between bolt and plate, and the local plate buckling-failure. In the further part of the paper only the connecting element type failure modes, (see figure 2a), are studied. The details of the experimental program and results can be found in [1].

3 PREDICTION METHOD FOR THE CYCLIC BEHAVIOR

In parallel with the experimental research a semi-empirical method is developed to predict the hysteretic behavior of the joints. In the first step, the method defines the typical hysteretic cycle belongs to the behavior mode. In further steps, by applying the standard cyclic loading [2], the hysteretic diagram is built up by multi-linear hysteretic cycles. The degradation tendency during the consecutive cycles is expressed by performance coefficient, which is experimentally determined by the linearized degradation of the rigidity. The proposed method is able to approximate the cyclic response and the absorbed energy of the studied joints for each observed failure mode types. It is based on the knowledge of the behavior curve, which can be established by monotonic experimental test, by standard based design method or by finite element simulation. The prediction method is developed on both the force-displacement and moment-rotation relationship levels, in this paper the results of the predicted cyclic behavior is based on the monotonic force-displacement diagram evaluated by the FE model detailed in chapter 4. The details of the prediction method are presented in [3], here only a short summary is given.

3.1 Typical hysteretic cycle

An example of the typical cycle for end-plate type behavior is presented in figure 3. The linear polygonal approximation of the cycles achieves good coincidence, as shown in figure 3b). The tangents of the polygonal lines of the typical cycles are derived from experimental observations in the function of the initial rotational stiffness of the monotonic curve. The model uses performance coefficient to include the peculiarities of each behavior mode type, which are defined as representing parameters for the failure mode types and calculated form experimental results. The proposed method follows the cyclic behavior in stable plastic cycles (cycles between the yield limit and cycles with significant resistant degradation).

The approximation of the cycle starts from the (F_{1p}, Δ_{1p}), point of the monotonic curve, with the determination of the unloading path (from F_{1p} to $F = 0$) and the loading path of the negative direction (from $F = 0$ to $-F_{1p}$) by experimentally based performance coefficients, reaching the negative part of the monotonic curve. The unloading path, coming from $-F_{1p}$ is also determined by the performance coefficients. The loading path of the positive direction reaches the monotonic curve at the rotation level Δ_2, which is determined according to the applied loading history. The hysteretic curve can be calculated cycle by cycle using the above detailed process.

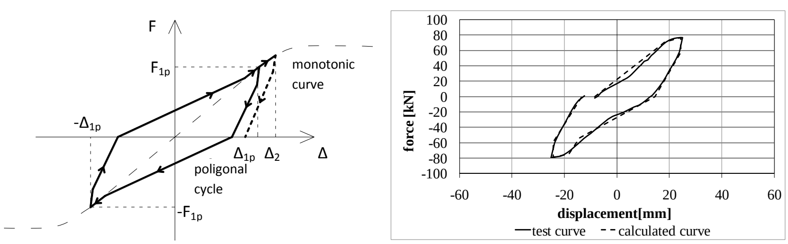
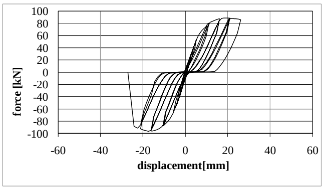


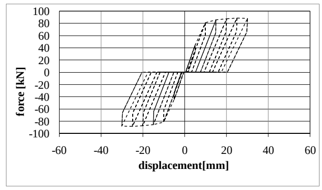
Figure 3: Typical hysteretic cycle.

3.2 Predicted moment-rotation relationship

The developed prediction method is applied by using the FE model based monotonic curve to predict the cyclic response of the joints. From this monotonic curve the hysteretic diagram is calculated cycle by cycle applying the ECCS [2] loading history. The calculated hysteretic diagrams of the connecting element type failure modes, (see figure 2a), are presented in figure 4, which show good coincidences with the experimental curves.

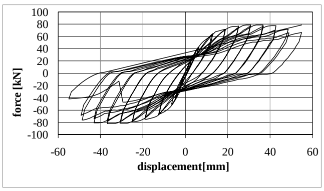


experimental

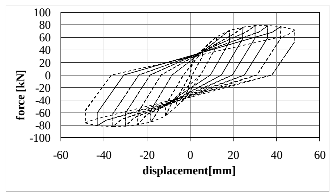


predicted

a) bolt-failure



experimental



predicted

b) plate-failure

Figure 4: Predicted and experimental hysteretic force-displacement curves.

The absorbed energy ratio of the consecutive hysteretic cycles is established from the predicted curves based and compared with the absorbed energy ratio of the corresponding experimental results. In case of the connecting element type failure the absorbed energy ratio is slightly overestimated by the prediction method, the difference between the predicted and the tested vales are between 1-18%. The details of the prediction method and results can be found in [3].

4 FINITE ELEMENT MODEL

In parallel with the prediction method an advanced finite element (FE) model has been developed using the ANSYS program, as shown in figure 5. The steel section is modeled by the 3D 8-node structural solid elements (SOLID185) having three degrees of freedom at each node. The concrete infill between the flanges of the I-section is modeled by 3D 8-node reinforced concrete solid element, which is capable of cracking in tension and crushing in compression, having three degrees of freedom at each node (SOLID65). The contact between the steel elements is modeled by contact pairs (CONTA174 and TARGE170) located on the surface of the 3D solid elements. Contact pairs are defined between the end-plate and the supporting plate; under the bolt head and nut, and surrounded the bolt shanks.

The material properties of the FE model are based on experimental material tests. For the steel I-section and bolts multilinear isotropic hardening material is used. In case of the studied joint geometry the failure occurred in the connecting element without significant damage of the composite beam, the cracking and crushing of the concrete material is avoided.

The support is defined by DOF constraints under the supporting plate at each node (see figure 5). In the FE analysis a displacement control is used to evaluate the monotonic force-displacement relationship of the specimens, which assumed to be the envelop curve of the experimental cyclic diagram.

The FE model is built up by input file using variables for all the geometry and material properties to prepare it for parametric analyses. The FE model is verified qualitatively by failure modes, as shown in figure 6, and quantitatively by the force-displacement relationship, as shown in figure 7.

The verified FE model is applicable for cyclic loading conditions and results in hysteretic force-displacement relationship, however it requires significant computation time. For this reason, it is decided to evaluate the monotonic force-displacement relationship and the prediction method is used for approximation of the hysteretic curve. A parametric study is performed with this method, as detailed in chapter 5.

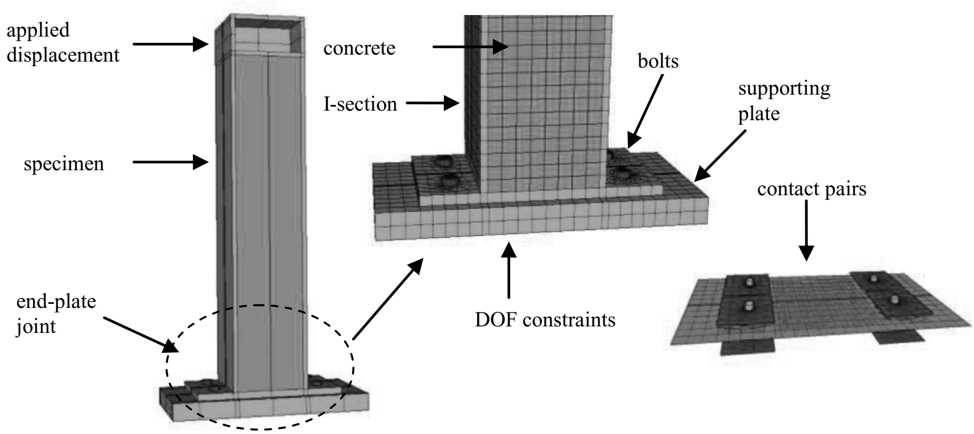
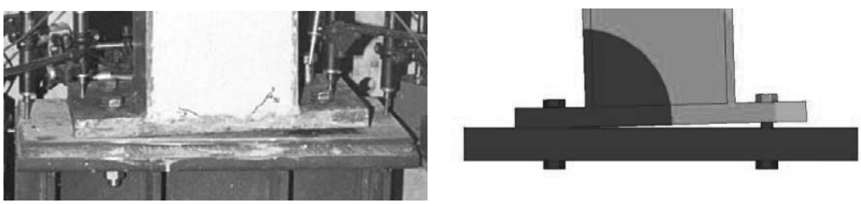
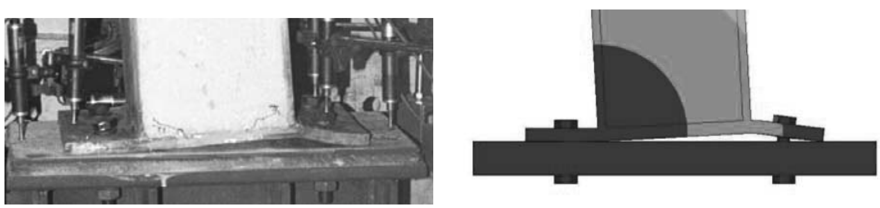


Figure 5: Details of the FE model.

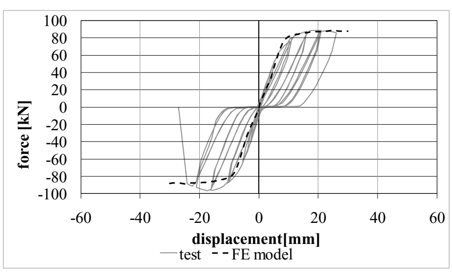


a) bolt-failure (specimen CCB1)

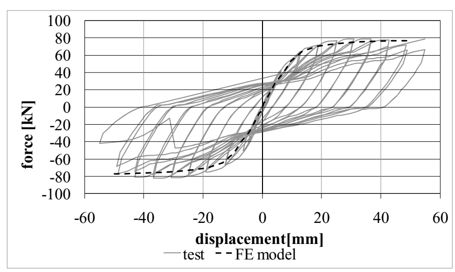


b) plate-failure (specimen CCB2)

Figure 6: Comparison of the failure modes.



a) bolt-failure



b) plate-failure

Figure 7: Comparison of the force-displacement relationships.

5 PARAMETRIC STUDY

The prediction method is applied in combination with verified finite element model to complete an extended parametric study. The parametric study examines bolted end-plate type connections remaining in the global geometry of the tested joint. Within this geometrical limitation the influence of the characterizing parameters – end-plate thickness, bolt size – is investigated on the resistance, initial stiffness and absorbed energy. It is assumed the section of the connecting composite member has resistance enough to avoid the local buckling failure of the member interacting zone.

In the presented parametric study the end-plate thickness is altering between 8-30 mm increased by 2mm, the bolts are between M10-M27, the grade of the steel, the bolt and the concrete materials are constant in each case and come from experimental material tests. The parametric study is performed on 84 specimens covering the whole parameter rage (end-plates t=8, 10, 12, 14, 16, 18, 20, 22, 24, 26, 28 and 30 mm; bolts M10, M12, M16, M20, M22, M24 and M27).

5.1 Monotonic force-displacement relationship

Finite element analyses are used to determine the monotonic force-displacement relationships of the joints for all the various parameters. Displacement control is used for each specimen and 30 mm maximal displacement is applied at the top of the specimen (see figure 5). The reaction forces occurred on the DOF constrains are detected and summarized in each load step and the monotonic (reaction) force-(applied) displacement curves are derived. As an example the monotonic relationship for bolt size M16 and end-plate thickness t=8-30 mm is shown in figure 8.

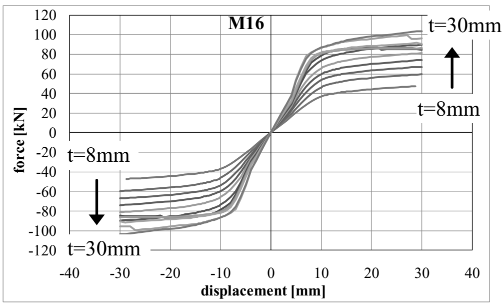


Figure 8: Monotonic force-displacement relationships.

The result of the monotonic FE analyses leads to the following input values of the prediction method: failure modes (bolt-failure or plate-failure), monotonic force-displacement curve, resistance, initial stiffness, yield limit. The failure modes of all the 84 specimens covering the parameter range are summarized in table 1.

Table 1: Failure modes.

end-plate thickness [mm]	8	10	12	14	16	18	20	22	24	26	28	30
M10	plate	plate	bolt	bolt	bolt	bolt	bolt	bolt	bolt	bolt	bolt	bolt
M12	plate	plate	plate	plate	bolt	bolt	bolt	bolt	bolt	bolt	bolt	bolt
M16	plate	plate	plate	plate	plate	plate	bolt	bolt	bolt	bolt	bolt	bolt
M20	plate	plate	plate	plate	plate	plate	plate	plate	bolt	bolt	bolt	bolt
M22	plate	plate	plate	plate	plate	plate	plate	plate	plate	plate	bolt	bolt
M24	plate	plate	plate	plate	plate	plate	plate	plate	plate	plate	bolt	bolt
M27	plate	plate	plate	plate	plate	plate	plate	plate	plate	plate	bolt	bolt

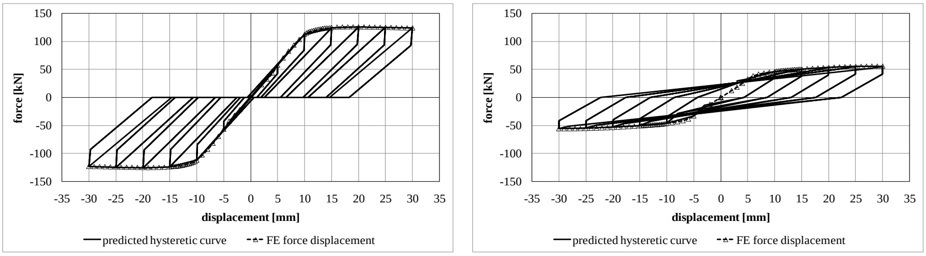
5.2 Predicted hysteretic curves and absorbed energy

On the basis of the monotonic curves the hysteretic behavior is derived by the developed prediction model, cycle by cycle, depending on the failure modes. The load history of table 2 is applied for each case, to have comparable results for each different parameter. At each displacement level two cycles are performed (e.g. cycle 1 and cycle 1 rep.).

Table 2: Cyclic load history.

Plastic cycle	1	1 rep.	2	2 rep.	3	3 rep.	4	4 rep.	5	5 rep.
Displacement [mm]	+10 -10	+10 -10	+15 -15	+15 -15	+20 -20	+20 -20	+25 -25	+25 -25	+30 -30	+30 -30

The hysteretic diagrams are evaluated for all the 84 specimens using an automated algorithm. As an example the predicted hysteretic curves of the two different failure modes are presented in figure 9; from the wide parameter range the following values are chosen for presentation: t=26 mm, M20 for bolt failure and t=14 mm, M12 for plate failure.



a) bolt-failure (t=26 mm M20)   b) plate-failure (t=14 mm M12)

Figure 9: Predicted hysteretic curves.

The predicted curves are performed with the aim to evaluate the absorbed energy of each specimen in the plastic cycles and to compare them to each other. In evaluation of the cyclic characteristics the calculation of the absorbed energy ratio is completed by recommendation of the ECCS [2]. The absorbed energy ratio can be calculated for each cycle as the ratio of the actual value and an ideal value, which could be measure in case of an ideal linear–perfectly plastic behavior. The absorbed energy ratio is approximately 0,6-0,7 for plate-failure specimens and 0,1-0,3 for bolt-failure specimens. For the comparison not the ratio, but the actual value of the absorbed energy, namely the area of the hemicycle of the force-displacement relationship is used with the unit [$kN \cdot mm$]. The absorbed energy is evaluated for each specimen in each cycle, an example the absorbed energy in cycle 4 and cycle 4 rep. are presented in figure 10. Similar tendencies of the absorbed energy of all the 84 specimens are observed in other plastic cycles.

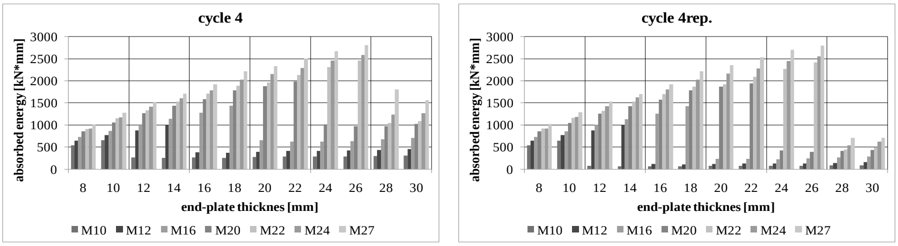


Figure 10: Absorbed energy.

In figure 10 the failure modes of the specimens are visible through the absorbed energy. Relatively high absorbed energy in both the cycle and the repeated cycle show plate-failure. The relatively small absorbed energy, which drop down in the repeated cycle due to the rigid body type rotation of the specimen means bolt failure. From figure 10 the end-plate thickness (t) and bolt size (d) parameter pairs can be selected for the favorable plate type failure in accordance with the required absorbed energy. The parametric study covers the d/t=0,33÷3,38 parameter range. Bolt-failure with very limited absorbed energy observed when d/t≈0,33÷0,96. The favorable plate-failure occurs with large energy absorption capacity due to the excessive deformation of the end-plate in parameter range d/t≈0,85÷3,38. In generally (see figure 10) using one size larger bolts leads to approximately two or three times larger absorbed energy capacity, due to modifying the failure mode to plate failure. This increasing tendency is even more significant in the repeated cycle, in extreme case it is four times larger for plate-failure than for bolt-failure (see figure 10) and still increasing in further repeated cycles.

6 CONCLUDING REMARKS

The presented analytical study on end-plate type joint of composite members has a strong experimental background. The experimental tests were performed in cooperation between the Budapest University of Technology and Economics and the Technical University of Lisbon. Based on the experiences of the experimental tests an advanced finite element model is developed and used for parametric study to evaluate the monotonic behavior of the end-plate joints, not excluded the global geometrical range of the test. The FE model is capable to evaluate the cyclic response of the specimen, however, it takes long computation time. To cover a wide parameter range it is decided to evaluate the monotonic response by FE analyses in combination of the developed hysteretic prediction method.

The completed parametric study covers 84 specimens and based on the evaluated absorbed energy efficient joint details from cyclic point of view are determined.

The presented FE model runs from an input file and all the geometrical and material properties are defined by a variable. This means that parametric study altering other variable (e.g. bolt and steel grade, distance of the bolts, size of the end-plate etc.) after certain adjustment of the mesh is applicable and the monotonic force-displacement relationship is available. The method to predict the hysteretic curve uses automated algorithm to evaluate the predicted hysteretic curve.

In this paper only the connection type behavior is studied. From the results the d/t ratios leading to favorable absorbed energy are determined and can be used in design practice. The further step of the research is to improve the FE model to be able to take into consideration the local buckling type behavior of the composite member interacting zone.

ACKNOWLEDGEMENT

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