COMPDYN 2013
4th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, V. Papadopoulos, V. Plevris (eds.)
Kos Island, Greece, 12–14 June 2013

SEISMIC BEHAVIOUR OF THE BEAM-TO-COLUMN DOWEL CONNECTIONS: FEM ANALYSIS

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Keywords: Seismic behavior, precast industrial buildings, dowel connection, FE model

Abstract. *To analyze the failure mechanism of the typical precast beam-to-column dowel connection, the numerical model in the FEA software ABAQUS [8] was defined and calibrated using the results of the experimental investigations. Cyclic as well as monotonic response was analyzed. The most important observations are: 1) standard theory assuming that the failure mechanism is initiated by flexural yielding of the dowel and crushing of the surrounding concrete has been confirmed [5-7]; 2) the strength of the connection considerably depends on the depth of the plastic hinge in the dowel, 3) in the case of the cyclic loading the strength is reduced due to the smaller depth of the plastic hinge, 4) neoprene bearing pad can considerably increase the strength of the connection, particularly when large relative displacements between the beam and the column are developed. The proposed FEM based tool supports additional parametric studies and the analysis of the buildings damaged in the recent European earthquakes.*

1 INTRODUCTION

Although the dowel type of the connection is the most common in Europe, the knowledge about its seismic behavior was incomplete and poorly understood. The connections were investigated only on simplified models where many important structural components were neglected. The lack of knowledge reflected in the seismic codes and in particular in the design practice. When the capacity design had become mandatory it became obvious that the existing knowledge about the behavior of realistic dowel connections was insufficient. The recent experimental research [1, 2, 3] on realistic connections provided more empirical data, however the mechanisms of failure have still not been adequately explained. For this reason a FEA model and a macro model supported by the FEA model were developed. In this article, the FEA model is presented while the macro model is described in companion article - Seismic Behavior of the Beam-to-Column Dowel Connections: Macro Modeling [4].

2 PREVIOUS STUDIES OF THE DOWEL FAILURE MECHANISM

Behavior of the precast beam-to-column connections analyzed in this paper is mainly characterized by the dowel action mechanism for which simplified numerical models assuming idealized conditions have already been developed in some previous studies [5-7].

If the dowel is located relatively far from the edges of the connected beam and column (the distance from the edge is more than six diameters of the dowel), it can be assumed that the strength of the dowel is reached at simultaneous yielding of the dowel and crushing of the surrounding concrete (see Fig. 1).

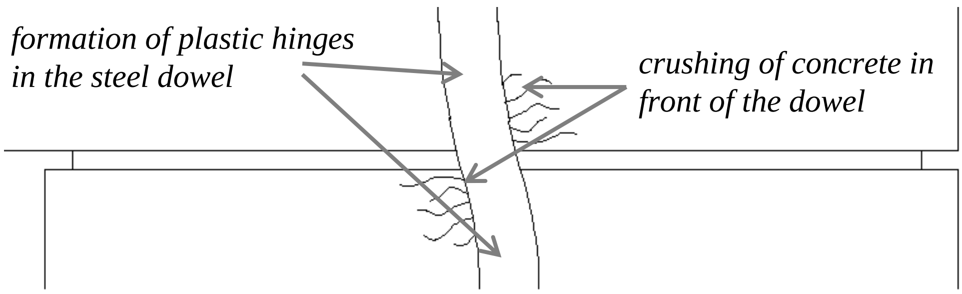

Figure 1: Failure mode of the dowel mechanism

If the concrete compressive strength, the steel yield strength and the diameter of the dowel are known, the following expression, according to [6, 7], can be used to analytically evaluate the ultimate resistance of the dowel connection at monotonic loading:

$$R_{u,m} = F_{u,m} = 1.3 \cdot {d_b}^2 \cdot \sqrt{f_{cc} \cdot f_y} = Fu, \tag{1}$$

f_{cc} $[MPa]$ ... *uniaxial compressive strength of concrete*

f_y $[MPa]$ ... *yield strength of steel*

Expression (1) is appropriate only for monotonic loading. In the case of cyclic loading, the capacity of the connection is notably lower due to the cyclic degradation of concrete and steel. In [6] the following formula is proposed to account for the decrease of the dowel ultimate resistance in the case of cyclic loading:

$$R_{u,c} = 0.5 \cdot R_{u,m} = 0.65 \cdot {d_b}^2 \cdot \sqrt{f_{cc} \cdot f_y}, \tag{2}$$

Based on the results of the experiments performed in the frame of the SAFECAST project (see [1, 2] and Section 3), a modified formulas have been proposed, which account for cyclic behavior of the realistic beam-to-column dowel connections:

$$R_{u,sr} = 1.1 \cdot {d_b}^2 \cdot \sqrt{f_{cc} \cdot f_y}, \tag{3}$$

$$R_{u,lr} = 0.9 \cdot {d_b}^2 \cdot \sqrt{f_{cc} \cdot f_y}, \tag{4}$$

$R_{u,sr}$ ... *ultimate resistance of the connection if small rotations between beam and column are expected*
$R_{u,lr}$ ... *ultimate resistance of the connection if large rotations between beam and column are expected*

It should be noted that the expressions (3) and (4) predict substantially higher resistance than formula (2). However, expressions (3) and (4) are predominantly empirical and no detailed analysis of the failure mechanism leading to this result was done within the SAFECAST project. Therefore the understanding of the behavior was incomplete and consequently the generalization of the formula to the cases not tested within the project was complex.

3 EXPERIMENTS

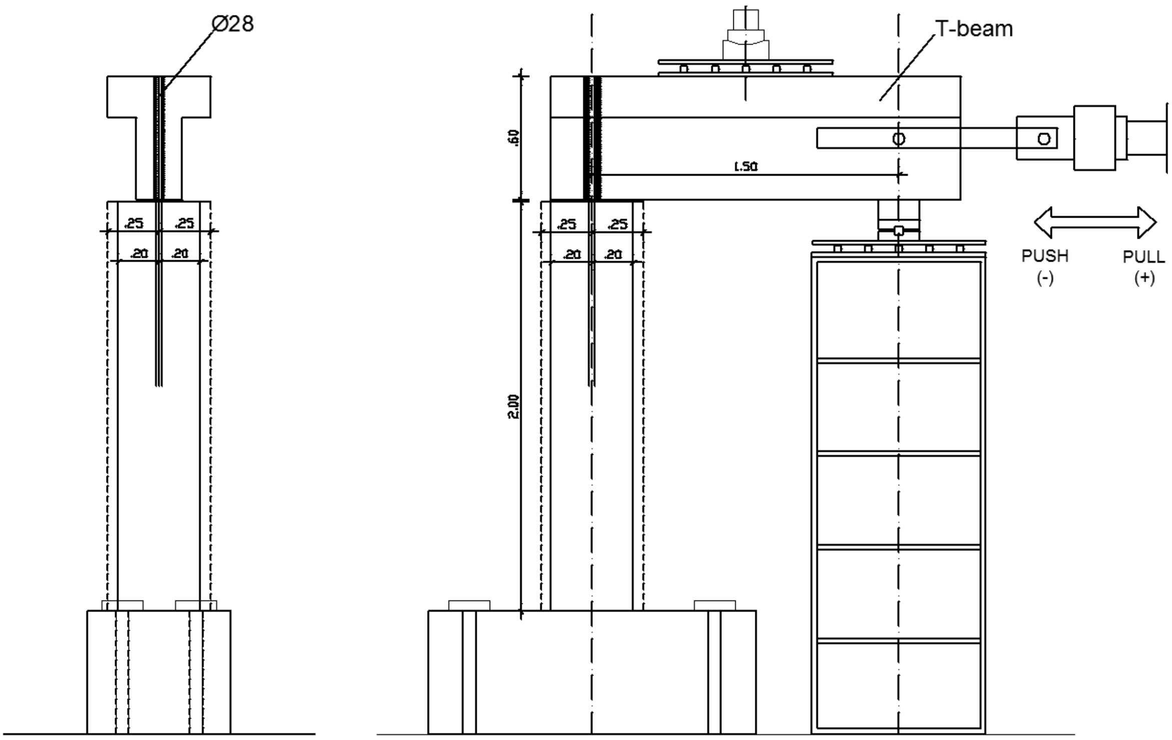

Figure 2: Scheme of the experimental set up.

The test set-up is shown in Fig. 2. The column was fixed to the ground through a special foundation, which was anchored to the laboratory floor. On the opposite side the beam was supported by a roller bearing, which allowed its horizontal movement. A vertical load was applied at the mid-span of the beam by means of a vertical hydraulic jack. The magnitude of the vertical load was 100 kN in all cases. The horizontal force was applied in the direction of the beam by means of another hydraulic actuator, attached to the reaction steel frame.

Vertical steel dowel of diameter Φ = 28 mm was located at the centre of the column cross-section. The dowel was anchored deep into the body of the column (90 cm) and protruded into the steel socket within the beam. The empty space between the dowel and the socket was filled with a fine non-shrinking grout (f_{ck} =15 - 20MPa). The neoprene pad (the thickness was 10 mm) was placed between the column and the beam in order to enable the relative rotations between the elements.

The T-shape beams were 60 cm high and 22/50 cm wide. At the location of the connection they were provided with a steel tube (80/50/2 mm) which was surrounded by a number of horizontal U-shape stirrups (Φ10/10 cm). The purpose of these stirrups was to partly confine the dowel and first of all to provide resistance against the splitting of the beam. For this reason, two additional stirrups of larger diameter (Φ14) were applied at the bottom of the beam. Similarly, the hoops in the beam (perpendicular to these stirrups) were closely spaced (Φ8/5 cm) within the location of the connection at a distance of 50 cm from the edge of a beam.

The columns had a square section (50x50cm). They were 2 meters high and therefore very stiff (small displacements of the column were expected). The confinement at the top of the column was substantial (Φ10/4 cm).

4 NUMERICAL MODEL

The specimen presented in Figures 3 and 4 was modeled using Abaqus FEA software [8]. The following structural components were included into the model: dowel, beam, column, infill, steel tube and neoprene bearing pad (Fig. 3). Modeling of each component is described in section 4.2.

To adequately simulate the experimentally observed response it was particularly important to properly model the connections between structural components listed above. Three different contacts were identified: dowel-to-concrete contact, dowel-to-grout contact and neoprene-to-concrete contact (Fig. 3). Modeling of the contacts is explained in detail in section 4.1.

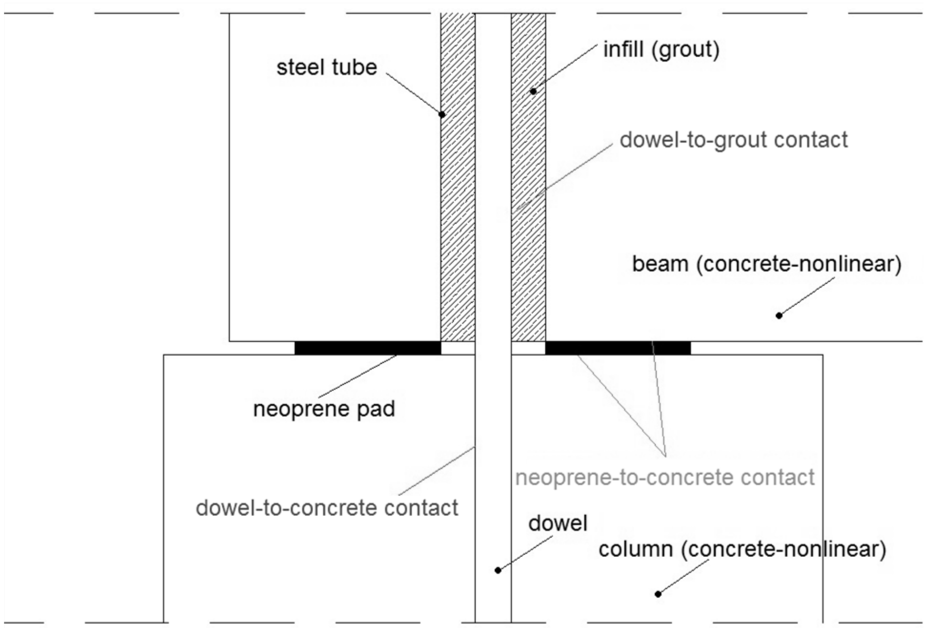

Figure 3: Close-up of the connection: presentation of the contact and material assignments

4.1 INTERACTION BETWEEN THE COMPONENTS OF THE CONNECTION

The contact properties were defined in two orthogonal directions. Hard contact with allowed separation was chosen normal to the surface of the dowel and the concrete. As it was observed during the experiment, the concrete around the dowel at the top of the column crushed and a crater-like void was formed around the dowel. This loss of the contact between the dowel and the concrete was properly modeled allowing their separation.

The tests described in section 3 showed no pull-out of the dowel. Nevertheless, tangential behavior was described with friction coefficient of 0.8 to simulate bond between the dowel and the concrete.

As long as the rubber pad is exposed to the normal pressure, there is a friction between the concrete and the pad activated, and the neoprene pad contributes to the shear resistance of the whole connection between the beam and the column. The interaction between the neoprene and the concrete surface was defined as a hard contact in normal direction and with a friction coefficient of 0.5 [9] in the tangential direction.

By assuming a totally rigid connection between the reinforcement and the surrounding concrete the slip of the reinforcement is neglected. For reinforcement, embedded elements were used to model total fixity to the surrounding concrete.

4.2 MATERIALS AND TYPES OF ELEMENTS

Material “concrete” as defined in Abaqus [8] was assigned to the beam and column. Material grout was assigned to the infill between the dowel and the steel tube. For the stress-strain relationship of concrete and grout Park & Kent model was used [10]. Nonlinearity of concrete was modeled by approaches based on the concepts of plasticity and damage by using Concrete Plasticity Damage Model (CPDM) included in ABAQUS [8]. All three parts (the beam, the column and the infill) were modeled with standard solid continuum elements with reduced integration C3D8R (an 8-node linear brick).

For modeling steel classical metal plasticity model (included in ABAQUS) with combined isotropic hardening, which uses Misses yield surfaces, was used. Stress and strain values were obtained from uniaxial tension test. The dowel was modeled with standard solid continuum elements with reduced integration C3D8R. For the reinforcement, 2-node linear 3D truss elements were used.

Because no tests have been performed to obtain the stress-strain diagram of the steel tube, bilinear response with maximum strength of 250 MPa and maximum deformation of 10% has been considered.

Neoprene bearing pad was modeled as an ideally elastic material with elastic modulus E=3MPa and Possion's ratio ν=0.49. Standard solid continuum elements with reduced integration C3D8R were used.

5 COMPARISON OF THE EXPERIMENTAL AND NUMERICAL RESULTS

In this section the efficiency of the proposed numerical model is demonstrated. The numerical results obtained by ABAQUS are compared with the test data. Good match with the experimental results was achieved on the global level as well as in all significant details. The comparison of the numerical and experimental relation between the horizontal force F_h in the actuator and the relative displacement between the beam and the column u_r is presented in Fig. 4.

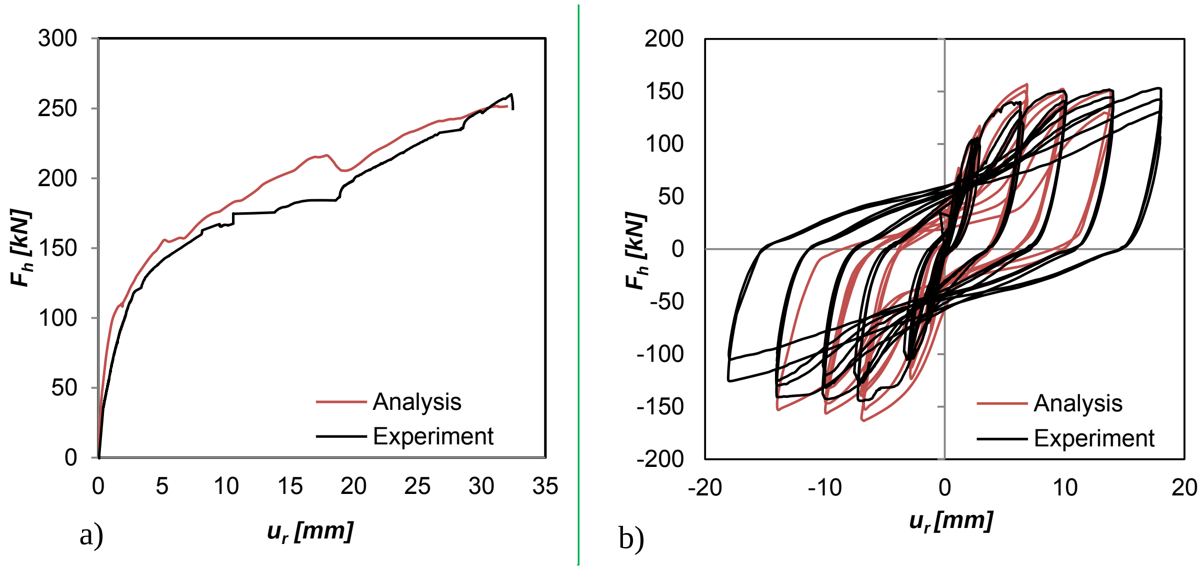

Fig. 4: (a) Global response (horizontal force –relative displacement): Comparison of the experiment and the analysis (a) for monotonic loading and (b) for cyclic loading.

The analysis successfully reproduced the mechanism observed during the test (Fig. 5(a)). First, the yielding of the dowel was observed, corresponding to the displacement of approximately 3 mm. Simultaneously the concrete around the dowel crushed allowing the dowel to develop large plastic deformation. The numerical model also captured well the experimentally observed cyclic strength deterioration (Fig. 5(b)).

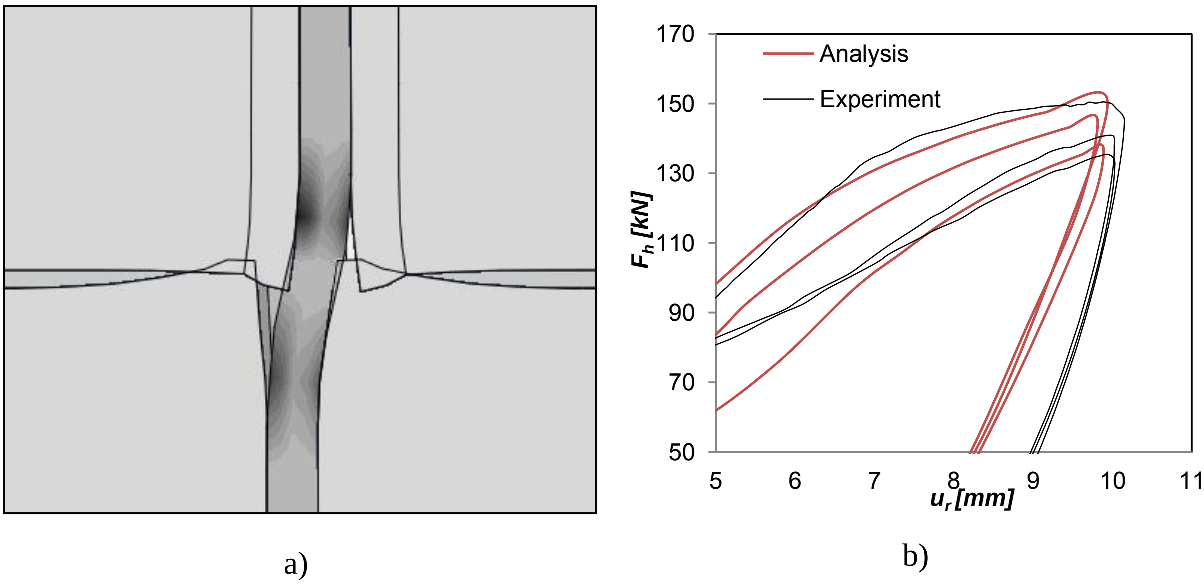

Fig. 5: (a) Failure of the dowel as predicted by the numerical analysis. (b) Experimentally observed cyclic deterioration was successfully captured by the model

The strain hardening in the case of monotonic loading (Fig. 4(a)) after the displacement of 20 mm was contributed by the neoprene pad, and the total strength of 250 kN was observed in the experimental as well as in the analytical response.

In the case of the cyclic response no hardening (typical for the monotonic response – Fig. 4(b)) was observed, neither in the analysis nor in the experiment. This was because of the smaller contributions (10% of the total force) of the elastomer to the total shear strength due to smaller relative displacements between the beam and the column. Additionally, the depth of the plastic hinge was smaller than in the case of monotonic loading, therefore smaller strength was obtained. Consequently the final difference of the monotonic and cyclic resistance was about 40%.

6 CONCLUSION

The research presented in this paper has provided a numerical tool, based on the ABAQUS FEA software, which is able to describe the characteristics of inelastic seismic behavior of dowel connections on the global and component level. Comparisons with experimental results obtained with monotonic and cyclic tests on realistic connections demonstrated the soundness and efficiency of the proposed model. Considering the complexity of the problem the match of the results is very good. The model was able to explain the failure mechanism as well as the most important features of the monotonic and cyclic response on the component level. It therefore helped to develop a less computationally demanding macro model presented in the accompanying paper - Seismic Behavior of the Beam-to-Column Dowel Connections: Macro Modeling [4].

7 ACKNOWLEDGEMENTS

The presented research was supported by the SAFECAST project “Performance of Innovative Mechanical Connections in Precast Building Structures under Seismic Conditions” (Grant agreement no. 218417-2) in the framework of the Seventh Framework Programme (FP7) of the European Commission. Experiments were completed at the Slovenian National Building and Civil Engineering Institute (ZAG). The specimens were constructed at Primorje d.d. company.

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