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Nonlinear finite element modelling of centric dowel connections in precast buildings

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Abstract. The modelling approach in the case of connections in precast buildings is specific. The assembly of the constitutive parts of the connection requires the inclusion of contact definitions in the model. In addition, the material non-linearity including the influence of the spatial stress distribution should be taken into account where appropriate. Here a complex model of a beam-to-column dowel connection is presented. Experiments on the analysed connection were performed within the framework of the European project SAFECAST (Performance of Innovative Mechanical Connections in Precast Building Structures under Seismic Conditions). Several material and interaction parameters were investigated and the influence of each of them was evaluated. The set of parameters which gave the best match with the experiments was chosen.

Keywords: dowel connection; precast buildings; concrete modelling; CDP model; interaction modelling; failure mechanism; failure analysis

1. Introduction

The modelling of the beam-to-column dowel connections in precast industrial buildings is a complex task as it is necessary to adequately model the concrete, the steel elements (the reinforcement and the dowels) and the neoprene bearing pad. Even of greater importance than the modelling of the elements themselves is the modelling of the interaction between them. In this aspect the modelling of precast structures is different from the modelling of the monolithic concrete structures. While in the latter case all the steel parts are typically supposed to be fully embedded in the concrete, this assumption is not appropriate for precast structures.

In the case of the dowel connection, which is commonly used in European design practice, it is of significant importance to take into consideration the relative displacements in the tangential and normal direction between the steel dowel and the surrounding concrete.[1]

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Furthermore, the behaviour of the concrete itself is very complex due to cracking, stiffness recovery, anisotropy, confinement effects etc. Moreover, the contribution of the neoprene bearing pad should not be neglected, as has been already revealed in some previous studies (LESSLOSS 2003, Magliulo *et al.* 2010, Magliulo *et al.* Zoubek *et al.* 2013).

The definition of the parameters of the concrete material model (see section 2) and the parameters of the interaction properties for nonlinear finite element modelling (see section 4) is not straightforward. In fact, these parameters vary from case to case and it is usually necessary to support each decision with experimental testing. However, some of them are crucial for the response while others are not. It is therefore important to know which parameters have to be selected with caution and for which, just a rough approximation is sufficient. For this reason a series of analyses (see section 5) were run to correctly evaluate the effect of each parameter. For the analyses the ABAQUS finite element analysis software (ABAQUS 2011) was used.

The results of the finite element analysis were supported by the experiments (section 3) performed at the University of Ljubljana in the frame of the 7th EU Framework research project SAFECAST - "Performance of innovative mechanical connections in precast building structures under seismic conditions (2009 – 2012)" (SAFECAST 2012). The results of the project (SAFECAST 2012, Kramar *et al.* 2010, Fischinger *et al.* 2012, Psycharis *et al.* 2012) are an important progress in understanding the response of the dowel connections under seismic loading, however, the emphasis of the work done was not on the finite element modelling of such connections.

Some other studies also investigated the response of the dowel connections and their modelling. Zaghi and Saiidi (Zaghi and Saiidi 2010) numerically modelled pipe-pin two-way hinges in concrete bridge columns. The mechanism of failure was analysed in detail and some design recommendations were given. However, the importance of the interaction and the material parameters used was not evaluated.

Considering the concrete damaged plasticity (CDP) material model, which was used in the study presented in this paper, some authors explain the constitutive theory and capability of the model to realistically capture the response (Lee and Fenves 1998, Lubliner *et al.* 1989, Yu *et al.* 2010). These findings were tested here on the case of the connection in precast building.

2. Concrete damaged plasticity model

The CDP model's primary purpose is to capture the response of concrete structures subjected to cyclic or seismic loading. It was developed by Lubliner *et al*. (1989) and Lee and Fenves (1998). In this section, the aspects of the constitutive theory of the model (ABAQUS 2011), which are relevant for the here presented study, are explained in short with some physical explanation of the input parameters.

A scalar damaged elasticity is introduced to express the relation between Cauchy stress and strain (Eq (1)).

$$\boldsymbol{\sigma} = (1-d)\boldsymbol{D_0^{el}}:(\varepsilon - \varepsilon^{pl}) = \boldsymbol{D^{el}}:(\varepsilon - \varepsilon^{pl}) \tag{1}$$

where ε, ε^{el} and ε^{pl} are total, elastic and plastic strains.

In the equation (1) $\boldsymbol{D_0^{el}}$ stands for the initial (undamaged) elastic stiffness of the material while $\boldsymbol{D^{el}} = (1-d)\boldsymbol{D_0^{el}}$ is the degraded elastic stiffness. Scalar d is an important variable by which the stiffness degradation is taken into account. Its values range from 0 to 1. The factor $(1-d)$ reduces effective load-carrying area (Eq. (2))

$$\boldsymbol{\sigma} = (1-d)\bar{\boldsymbol{\sigma}} \tag{2}$$

where $\bar{\sigma}$ is the effective stress and σ is the Cauchy stress.

Scalar d therefore reduces the elastic stiffness of the material and increases the stresses by reducing the load carrying area.

The effective stress space defines the failure and the damage of the material. Mathematically it can be expressed with the following yield condition (Eq. (3)) (Lee and Fenves 1998):

$$\boldsymbol{F}(\bar{\boldsymbol{\sigma}}, \tilde{\boldsymbol{\varepsilon}}^{pl}) \leq \frac{1}{1-\alpha}\left(\bar{q} - 3\alpha\bar{p} + \beta(\tilde{\boldsymbol{\varepsilon}}^{pl})\langle\hat{\bar{\sigma}}_{max}\rangle - \gamma\langle-\hat{\bar{\sigma}}_{max}\rangle\right) - \bar{\boldsymbol{\sigma}}_{\boldsymbol{c}}(\tilde{\varepsilon}_c^{pl}) \leq 0 \tag{3}$$

In (3), $\bar{p}$, $\bar{q}$ and $\hat{\bar{\sigma}}_{max}$ are the effective hydrostatic pressure, the Mises equivalent effective stress and the maximum eigenvalue of $\bar{\sigma}$, respectively. The coefficients α and γ are dimensionless material constants and can be calculated with the expressions (Eqs. (4) and (5)):

$$\alpha = \frac{\sigma_{b0}/\sigma_{c0} - 1}{2\sigma_{b0}/\sigma_{c0} - 1} \tag{4}$$

$$\gamma = \frac{3(1-K_c)}{2K_c - 1} \tag{5}$$

The constants σ_{b0}/σ_{c0} (ratio between the equi-biaxial and uniaxial compressive yield stress) and K_c are the input parameters for the CDP model that indirectly define the loading surface in the deviatoric and hydrostatic plane, respectively. To precisely evaluate the parameters σ_{b0}/σ_{c0} and K_c, biaxial and triaxial compression tests (Lubliner *et al.* 1989) are needed. The influence of these two parameters is analysed in section 5.

If $\hat{\bar{\sigma}}_{max} < 0$, the yield condition (Eq. (3)) transforms to the following expressions (Eqs. 6, 7):

$$(\tfrac{2}{3}\gamma + 1)\,\bar{q} - (\gamma + 3\alpha)\bar{p} = (1-\alpha\,)\,\bar{\sigma}_c \tag{6}$$

$$(\tfrac{1}{3}\gamma + 1)\,\bar{q} - (\gamma + 3\alpha)\bar{p} = (1-\alpha\,\bar{\sigma}_c)\,\bar{\sigma}_c \tag{7}$$

If $\hat{\bar{\sigma}}_{max} > 0$:

$$(\tfrac{2}{3}\gamma + 1)\,\bar{q} - (\gamma + 3\alpha)\bar{p} = (1-\alpha\,)\,\bar{\sigma}_c \tag{8}$$

$$(\tfrac{1}{3}\gamma + 1)\,\bar{q} - (\gamma + 3\alpha)\bar{p} = (1-\alpha\,\bar{\sigma}_c)\,\bar{\sigma}_c \tag{9}$$

For clarification, the yield surface (visual presentation of eq. (3)) in plane stress is given in Fig. 1.

Other parameters which define the CDP model are the dilation angle (Ψ), eccentricity (ϵ), σ_{b0}/σ_{c0}, K_c and viscosity (μ). These parameters were chosen according to the suggested values from the ABAQUS manual (ABAQUS 2011) and previous studies (Zaghi and Saiidi 2010). The values were then varied to inspect the effect of each parameter on the global response of the connection (see section 5).

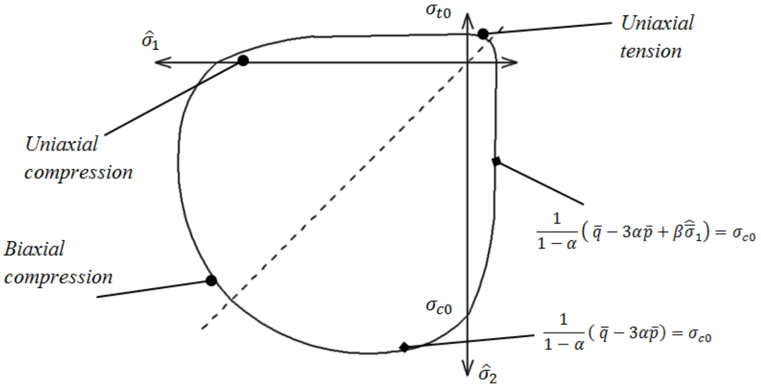
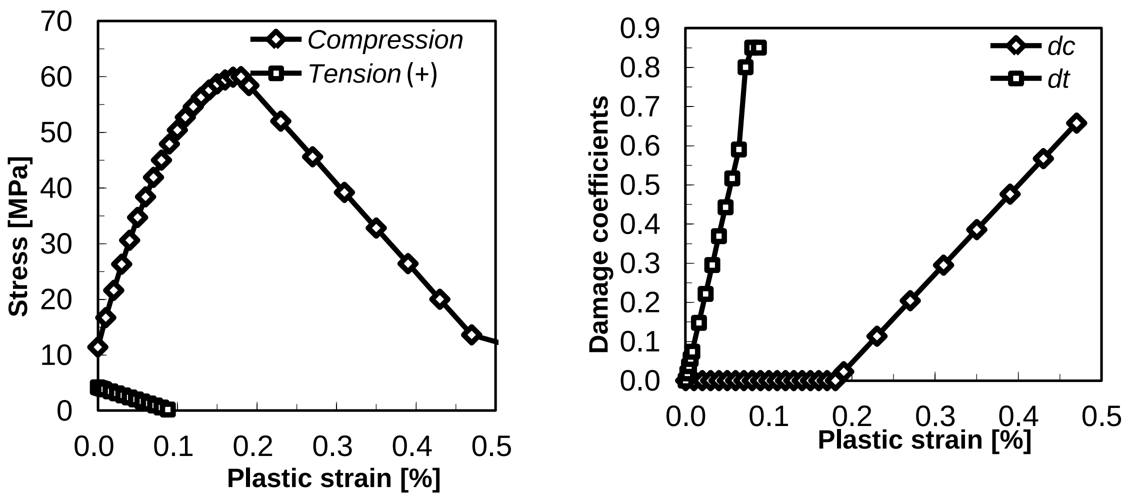


Fig. 1 Yield surface in plane stress



a) b)

Fig. 2 a) Uniaxial compressive and tension stress-strain diagram and b) the definition of the damage factors in compression (dc) and in tension (dt) used in the analysis

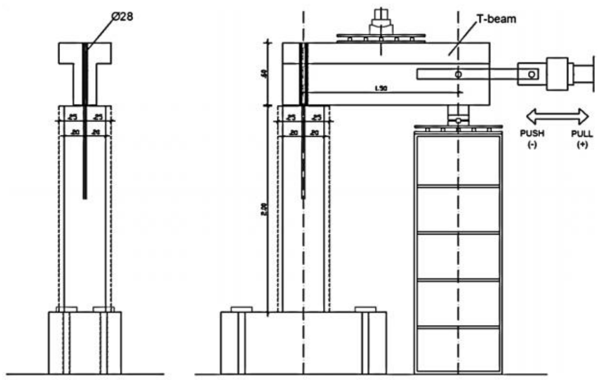


Fig. 3 Experimental set up

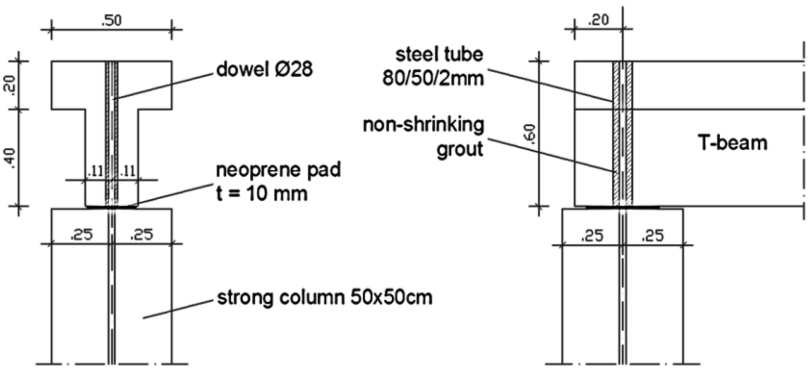


Fig. 4 Details of the connection

3. Overview of the experiments

Monotonic and cyclic tests of the dowel beam-to-column connections were performed at the University of Ljubljana in the frame of the SAFECAST project (SAFECAST 2012). The horizontal connection between the beam and the column was established by means of the vertical steel dowel with a large diameter (Φ28mm) protruding from the column into the beam. The dowel was anchored deep into the body of the column (90cm) and was placed through the end of the beam. A 1.0cm thick neoprene pad was placed between the column and the beam in order to enable the relative rotations between the elements. The columns were designed to be strong enough not to yield before the maximum load-carrying capacity of the dowel connection is reached (Fig. 4). The columns and the beams were constructed of high strength self-compacting concrete C45/55. All the reinforcing steel was class S500 B. The scheme of the experimental set-up is shown in Fig. 3. The detailed view is presented in Fig. 4. A more thorough description of the test can be found in (Zoubek *et al.* 2013, Kramar *et al.* 2010).

4. Modelling of the constitutive parts of the model and their interaction

In order to reduce the computational time, the model was later simplified by only including the parts in the regions close to the connection (Fig. 5 and 6). Seven components were included in the model: the concrete beam, the steel tube, the infill, the steel dowel, the neoprene bearing pad, the concrete column and the reinforcement.

The beam, the column and the infill were modelled as solid elements. 3D brick elements with reduced integration (C3D8R) included in ABAQUS (2011) were used. The average size of the concrete finite element was 2cm (Fig. 6). The concrete material model used in the analysis was the concrete damaged plasticity (CDP) model (see Section 2). The CDP model was used for the beam, the column and the infill (Fig. 3 and Fig. 6).

The boundary conditions defined on the beam and the column are presented in Fig. 6. At the bottom, the column was fixed while the beam was horizontally loaded. The vertical and perpendicular displacements of the beam were restrained on the same surface of the beam as the horizontal loading was applied (Fig. 6).

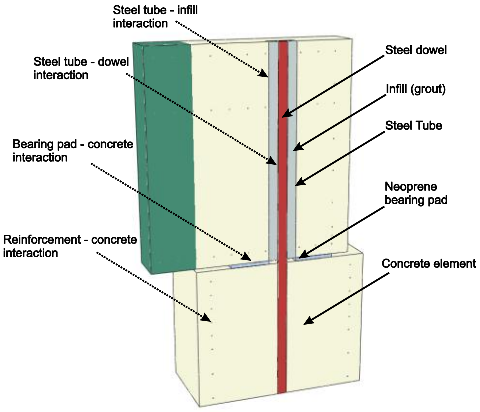


Fig. 5 Constitutive parts of the simplified model and the interactions between these parts

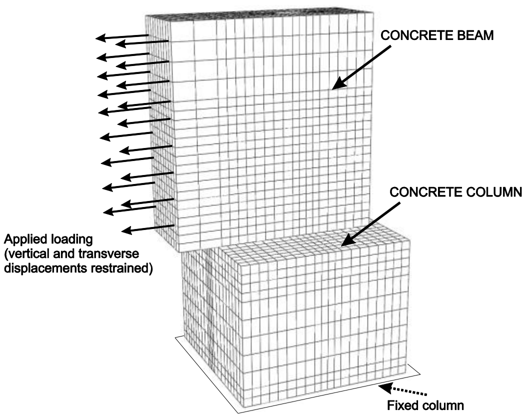


Fig. 6 Perspective view of the concrete parts of the model: the beam and the column

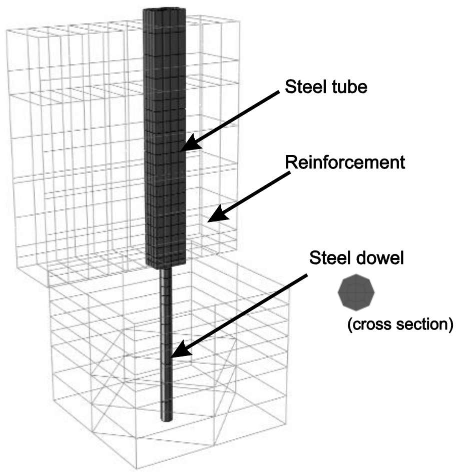
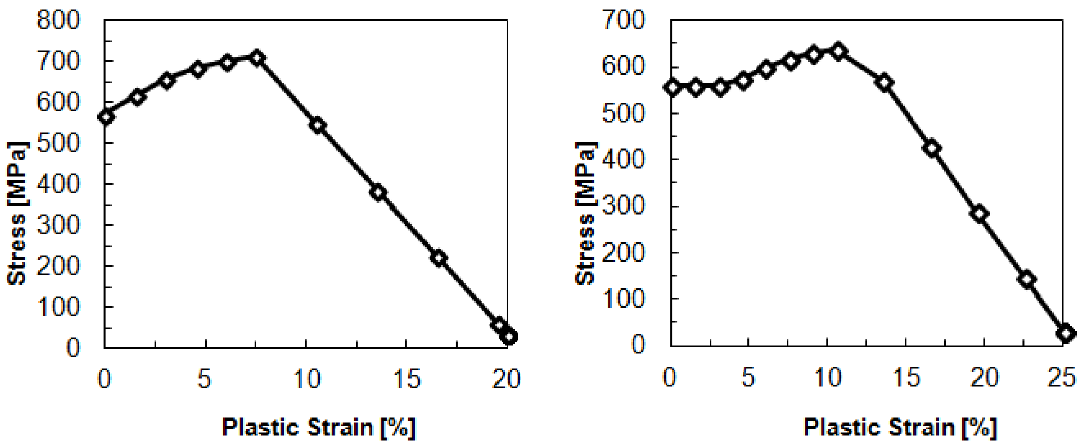


Fig. 7 Steel parts of the model: steel tube, reinforcement and steel dowel



a) b)

Fig. 8 Uniaxial tension stress-strain diagram for the steel dowel and the reinforcement

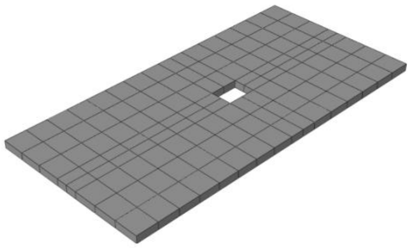


Fig. 9 Perspective view of the neoprene bearing pad

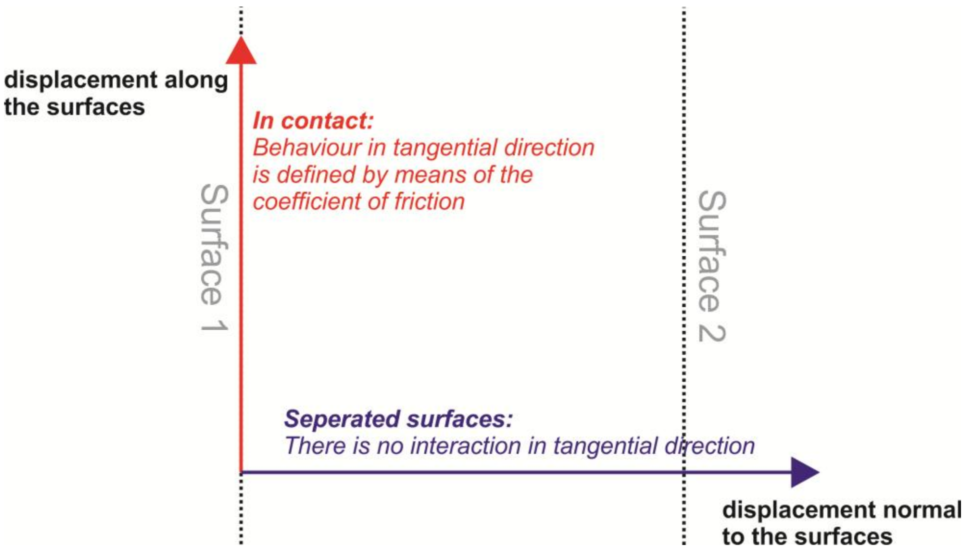


Fig. 10 The interaction model for the dowel-concrete and neoprene-concrete contacts

The model presented in this paper is only capable of capturing the response of the dowel connections where small relative rotations between the beam and column occur. In such cases, the column is strong enough not to yield before the maximum load-carrying capacity of the dowel connection is reached. The issue is explained in more detail in (Zoubek *et al.* 2013), where the more complex model, which can simulate the effect of the large relative beam-column rotations, is also presented.

The steel dowel was modelled with 3D brick elements with a reduced integration (C3D8R in ABAQUS). For the reinforcement, truss elements were used (Fig. 7). The steel tube was modelled with shell elements (S4 in ABAQUS). The size of the steel elements (dowel, tube or reinforcement) ranged from 2-3cm.

The behaviour of the steel elements is not the main objective of this paper, therefore only a brief description of the modelling will be given. For the reinforcement and the steel dowel a rate-independent plasticity with a Mises isotropic yield surface (von Mises 1913) was used. The input for this material model is the result of the uniaxial tension test of the steel (Fig. 8).

The neoprene bearing pad (Fig. 9) which is installed between the column and the beam was modelled using 3D brick elements with a reduced integration. A simple elastic material model with an elastic modulus of E=3MPa and Poisson's ratio ν=0.49 was chosen.

It was of significant importance to define the appropriate contact formulations between the constitutive components: steel tube – infill interaction, infill – dowel interaction, concrete beam – neoprene bearing pad interaction, concrete column – steel dowel interaction and concrete column – reinforcement interaction.

The interaction between the steel elements and the concrete parts was modelled using a small sliding formulation. In ABAQUS (2011) it is possible to define the contact conditions by identifying and pairing the potential contact surfaces. The small-sliding formulation was chosen for the interaction between the steel dowel and the concrete since the experiments demonstrated that large relative displacements did not occur.

In the direction normal to the surfaces of the dowel and the surrounding concrete, a hard contact with the allowed separation was chosen to describe the behaviour of the interaction (Fig. 10). In the tangential direction, the penalty friction formulation was chosen to model the friction between the dowel and the concrete (ABAQUS 2011) (Fig. 10). The friction coefficient between a steel bar and concrete ($k_{fr,d-c}$) depends on the roughness of the steel bar and is complex to define. The analysis gave the best match with the experiment if the value of 0.8 was chosen (see section 5).

The reinforcement of the beam and the column (see Fig. 7) was modelled as fully embedded in the concrete. This assumption should not adversely affect the results since the global response is mainly influenced by the dowel mechanism, as was observed during the experiments described in the previous section. The dowel mechanism is characterized by the local crushing of the concrete in front of the dowel and the simultaneous yielding of the steel dowel due to the large flexural deformations of the dowel at some depth in the concrete element. A detailed description of the mechanism can be found in (LESSLOSS 2003, Zoubek *et al.* 2011, Vintzeleou and Tassios 1986).

While large relative displacements are expected on the contact between the neoprene and the concrete surfaces, the finite-sliding formulation (ABAQUS 2011) is used. According to some experimental studies (Magliulo *et al.* 2010), a friction coefficient ($k_{fr,n-c}$) of 0.5 is appropriate. In the normal direction, hard contact with a permitted separation was chosen as in the case of the concrete-steel interaction described earlier (Fig. 10).

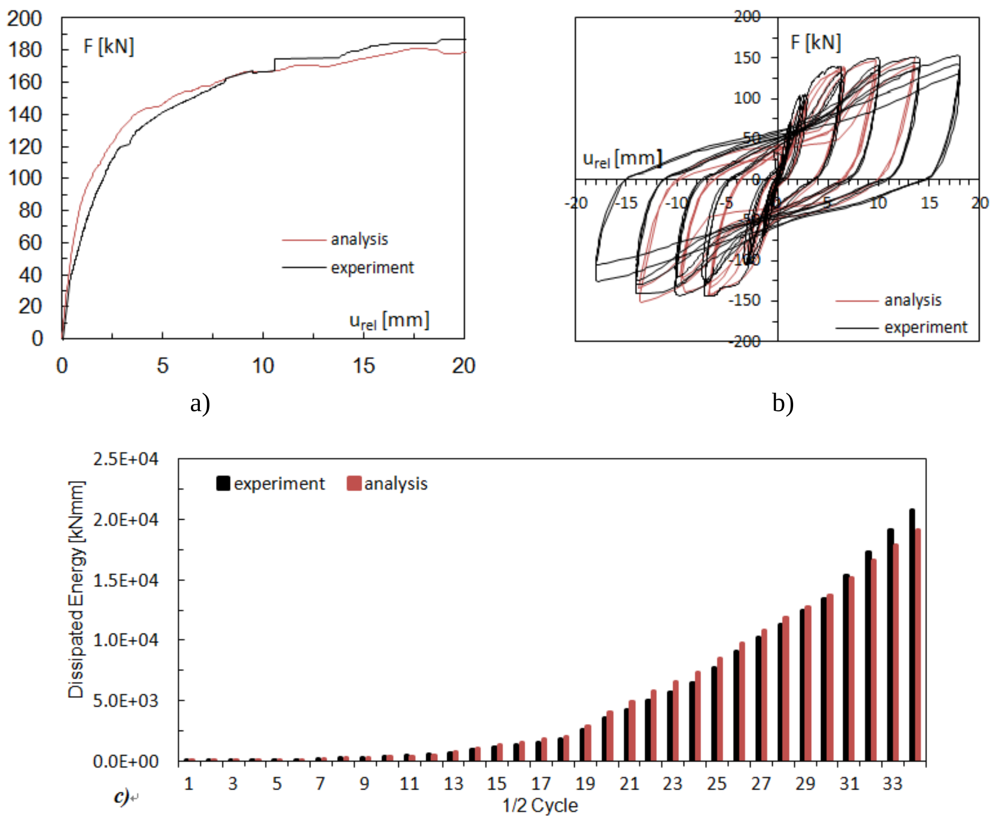
5. Parametric investigation for numerical modeling

In this section the influence of the different modelling parameters described in section 2 is investigated. First, the combination of the parameters which gives the best match with the experimental results is presented. Further on, diagrams that show the influence of different parameters are given. Three different probable values for each parameter were chosen and compared.

5.1 Comparison experiment-analysis (best match)

The best match with the experiment (Fig. 11) was achieved using the following parameters: $\Psi = 31°, \epsilon = 0.1, \sigma_{b0}/\sigma_{c0} = 1.16, K_c = 0.666, \mu = 0.001, k_{fr,d-c} = 0.8,\ \ k_{fr,n-c} = 0.5$.

For the monotonic loading, the response agrees quite well with the experiment (Fig. 11(a)). However, in the case of the cyclic loading, a somewhat larger pinching effect was observed during the analysis (Fig. 11(b)). This is due to the opening of the gap between the steel dowel and the surrounding concrete. The gap does not close immediately after the loading is reversed. Although pinching was not exactly modelled, the difference between the analytically modelled and the



(c)

Fig. 11 Comparison of the experimental and the analytical results for (a) monotonic and (b, c) cyclic loading experimentally observed dissipated energy is small (Fig. 11(c)). This can be explained by the higher forces reached in the analysis which increase the dissipated energy of the model. Furthermore, it should also be mentioned that the convergence problems occurred at the relative displacement of 15mm in the case of the cyclic loading. Nevertheless, the behaviour of the connection and its capacity were captured well enough to study the influence of the differentmodelling parameters in the following section.

It should be noted that the experimental response for the monotonic loading is not given up to the failure. The dowel failed after pulling it back in the opposite direction and then again pushing it up to the relative displacement of 30mm. In the case of cyclic loading, the connection failed at the relative displacement of 18mm, as shown in Fig. 11b.

5.2 Evaluation of different modelling parameters on the cyclic response

First, the influence of the dilation angle Ψ was analysed (Fig. 12). The values of 15°, 31° and 45° were tested (these values are often suggested by the users). According to the equation (11), the dilation angle affects the flow potential of the material model. It does not seem to have an important influence on the global response of the connection if cycling loading is applied.

Another parameter which defines the flow potential surface is the eccentricity ϵ. For the eccentricity ϵ, a value of 0.1 is usually chosen (ABAQUS 2011). However, here the values of 0.05 and 0.15 were also tested to examine the influence of this parameter on the global response. The effect of changing the eccentricity parameter was negligible (Fig. 13).

Fig. 14 shows the influence of the ratio σ_{b0}/σ_{c0} which defines the yield surface. The parameter does have an important role in modelling and should be dealt with with care. From the Eq. (4) it is obvious that an increase of σ_{b0}/σ_{c0} will result in a larger material constant α. This fact demonstrates that higher values of σ_{b0}/σ_{c0} will cause an expansion of the yield surface (please see Eq. (3)) and therefore a larger capacity of the dowel connection itself (Fig. 14). Typical experimental values for the ratio σ_{b0}/σ_{c0} range from 1.10 to 1.16.

Fig. 15 represents the global response for different values of another material constant K_c, ranging from 0.4 to 0.8. Regarding the results presented here, it is the most prominent CDP model parameter. In the case when value 0.4 was chosen, the connection failed already at the relative displacement of 12.5mm due to the early failure of the steel dowel.

Higher values of the coefficient K_c will cause a decrease in the parameter γ (please see Eq. (5)). Consequently the size of the concrete's yield surface increases (Eq. (3)). This results in a higher capacity of the connection characterized by the failure of the steel dowel (Fig. 15).

In Fig. 16, the influence of the viscosity μ is presented. This parameter improves the convergence but it can overestimate the capacity if too large values are chosen. The results of the analysis show that for this presented model, a value of 0.001 or less is adequate (Fig. 16). If a very small value was chosen (lower than 0.00001), the convergence problems occurred. However, the capacity did not seem to change much.

Fig. 17 and 18 show the influence of the coefficient of friction at the interactions dowel - concrete and neoprene - concrete. The diagrams indicate that a wrong assumption is made if the surfaces are assumed to be tied together as is normally the case when modelling monolithic structures (a perfect embedment of the dowel and a perfect adhesion of the neoprene pad to the concrete). The variation of the friction coefficient between the concrete and the neoprene (Fig. 18) did not affect the global response in the same amount as the friction coefficient between the dowel and the surrounding concrete (Fig. 17). Using a more complex model it was shown (Zoubek *et al.*

2013) that the influence of the friction coefficient between the concrete and the neoprene is much more important if the relative rotations between the beam and the column are taken into account and if axial loading is applied on the connection.

In the last series of the analyses the importance of the damage factors of the CDP model was evaluated. The damage factors mainly affect the response of concrete structures subjected to cyclic loading. The shape of the functions that describe the relationship between the damage and the plastic deformation in tension and compression (see Fig. 2(b)) remained the same in all three analyses. Only the amplitude of the damage varied. The maximum damage factor was limited to 0.85 (values closer to 1.0 cause convergence difficulties). The results show notably higher unloading stiffness degradation as well as strength degradation of the connection for higher values of the CDP model damage factors. If no damage is defined, the capacity of the cyclic response of the connection is overestimated. Therefore it can be concluded that neglecting the damage of the concrete will lead to the overestimation of the cyclic capacity of the connection.

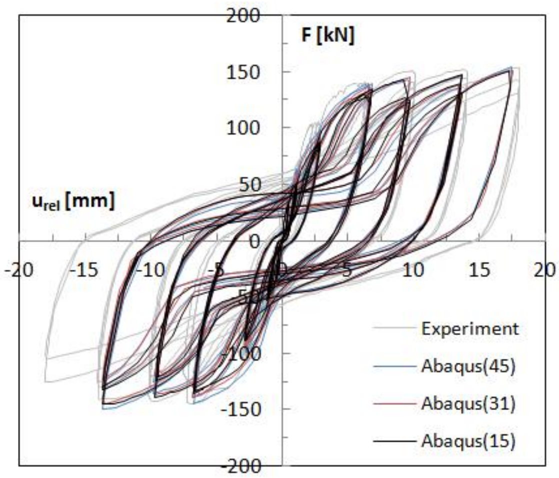


Fig. 12 Influence of the dilation angle Ψ on the global response of the connection

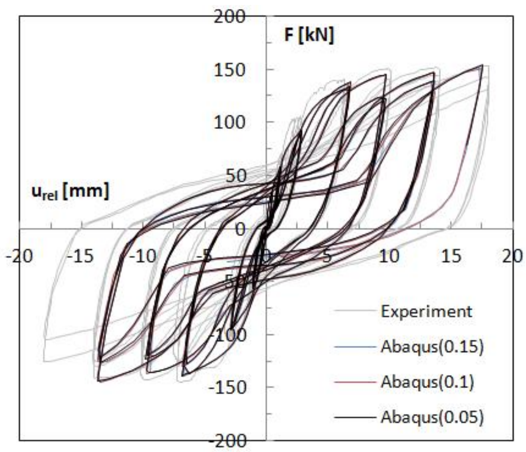


Fig. 13 Influence of the eccentricity ϵ on the global response of the connection

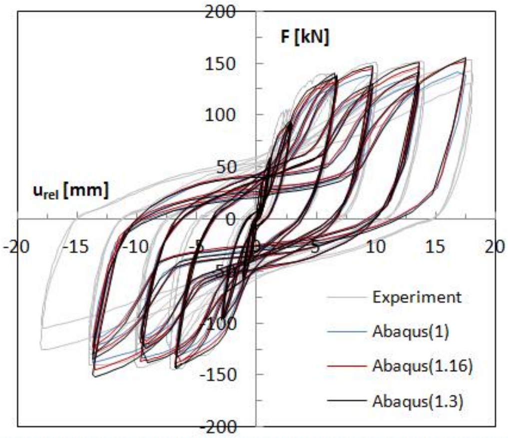


Fig. 14 Influence of the ratio σ_{b0}/σ_{c0} on the global response of the connection

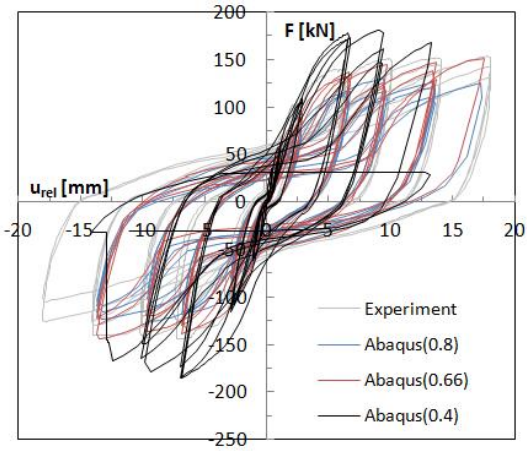


Fig. 15 Influence of the parameter K_c on the global response of the connection

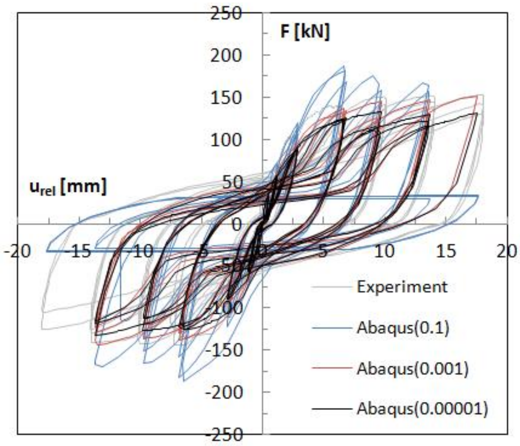


Fig. 16 Influence of the viscosity parameter μ on the global response of the connection

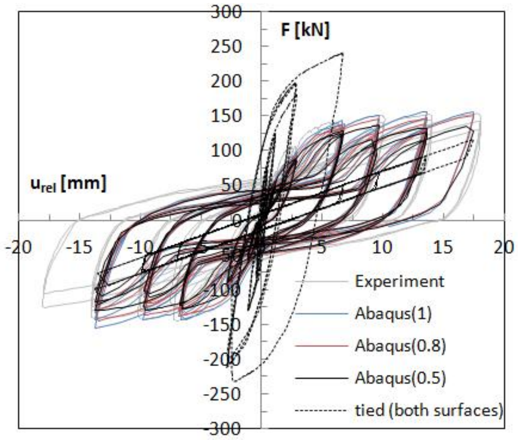


Fig. 17 Influence of the dowel-concrete friction coefficient on the global response of the connection

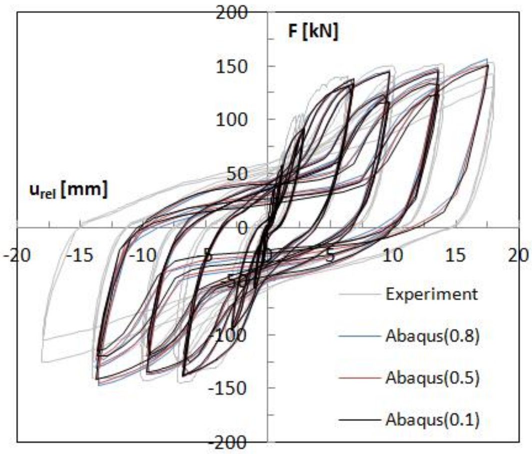


Fig. 18 Influence of the neoprene-concrete friction coefficient on the global response of the connection

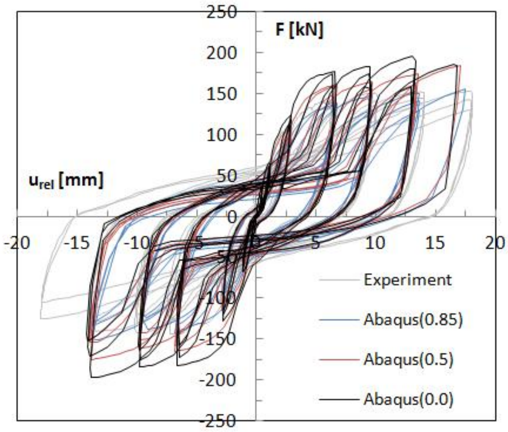


Fig. 19 Influence of the maximum damage factor on the global response of the connection

6. Conclusions

The complexity of the modelling of the dowel connections in precast buildings is inevitable since it is crucial to define proper models for the materials used (steel, concrete and neoprene) and equally important – assign appropriate interaction properties between different parts of the connection. For this reason, the assumptions normally used for modelling monolithic structures are not adequate in the case of precast structures, where often no noteworthy mistake is done if the relative displacements (e.g. slippage) between the concrete and steel elements are neglected.

In this study, several parameters which define the contacts between different components and materials, as well as the concrete material behaviour were investigated before the final model was proposed. Concrete damaged plasticity model parameters that influenced the response of the dowel precast connection the most were: σ_{b0}/σ_{c0} (ratio between the equibiaxial and uniaxial compressive yield stress), K_c and the viscosity μ. The influence of Ψ (dilation angle) and ϵ (eccentricity) which define the plastic flow was negligible. However, this was not the case when parameters σ_{b0}/σ_{c0}, K_c and μ were changed. The maximum force (F_u) in the connection varied by around 10% if the values of 1-1.3 were chosen for σ_{b0}/σ_{c0} and for 15-20% if K_c was defined in the range 0.4-0.8. The viscosity parameter (μ) may be used to ease convergence problems. However, a too high value will distort the results. More specifically, the predicted capacity will be too high if too much viscosity is added. Therefore, it is strongly recommended that the influence of the level of the viscosity used before the final model is offered is analysed. In this study, the values from 0.1 to 0.00001 were tested. F_u increased by approximately 25% from 150kN to 185kN if the viscosity factor was 0.1, which is obviously too high.

The interaction between the different components of the dowel connection was relatively simply modelled using a hard contact with an allowed separation in the normal direction and a friction coefficient in the tangential direction. For $k_{fr,d-c}$, values from 0.5-1 were analysed. F_u differed by 15%. If the dowel and the concrete were completely tied together the F_u was 60% higher (240kN instead of 150kN). Similar conclusions can be obtained when studying the influence of the interaction between the neoprene pad and the concrete. The assumption that the surfaces were completely tied together yielded an unrealistically large amount of stiffness and strength for the connection.

Considering the complexity of the concrete material model and the interactions between the different components of the connections, the best match with the experiment was if the following values were used for the parameters of the CDP model and friction coefficients: $\Psi = 31°$, $\epsilon = 0.1$, $\sigma_{b0}/\sigma_{c0} = 1.16$, $K_c = 0.67$, $\mu = 0.001$, $k_{fr,d-c} = 0.8$, $k_{fr,n-c} = 0.5$.

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