Cyclic Response of Dowel Connections in Precast Structures

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SUMMARY:
Precast buildings are frequently used in the design practice in Europe. However, the seismic response of one of their key structural elements - connections was poorly investigated. Even for the most commonly used dowel beam to column connections, the information about their seismic response was quite limited, particularly in the case of large relative rotations of beams and columns, which are typical for this type of structures. Therefore, the cyclic response of these connections was experimentally investigated. Two possible types of failure were identified: a) the failure of the dowel and b) the failure of the beam-column joint. Parameters, which control the type of failure, were identified. The strength degradation of 20% in the case of large relative rotations between columns and beams was observed. Based on the experimental results, a quite robust numerical non-linear macro-model of the investigated connections has been identified.

Keywords: precast buildings, connections, cyclic experiment, seismic response, numerical model

1. INTRODUCTION

Precast buildings have been frequently used in many European countries. Predominant type of these structures consists of an assemblage of columns tied together with beams. Among many types of different connections between precast elements, the connection using steel dowel is the most common. Nevertheless, the quantified knowledge of their inelastic response to earthquakes has been poor. This is partly due to the fact that the predominant mechanisms of the seismic response of the connections are complex and difficult to model. In practice connections are predominantly designed by engineering feeling and numerical verifications are seldom done.

In the previous researches (Toniolo, 2007; Fischinger, 2008) it has been recognized that very large rotations at the top of the slender columns in precast industrial buildings can be expected when they are subjected to strong earthquakes (Figure 1.1.). While in general the research of the cyclic (seismic) behaviour of the dowel connections has been very limited, there were no tests at all where such large relative rotations between columns and beams were taken into account.

Figure 1.1. Large deformations (8% drift) of the columns in precast industrial building tested at ELSA in Ispra within the PRECAST project (Toniolo, 2007)

The cyclic behaviour of the dowel connections was systematically experimentally tested on the series of full-scale models in the frame of the European project SAFECAST (SAFECAST, 2012). The main European associations of the precast manufacturers and different research institutions at the most earthquake prone areas in Europe, joint their efforts to define the design procedures for different types of connections in precast buildings. The supporting experimental campaign has been without comparison in the past. A large number of different connections (traditional, innovative, dissipative, connecting different structural elements) and structural assemblages in large scale have been tested. Monotonic, cyclic, PSD and shake table tests were performed.

The experimental research, preformed at University of Ljubljana (UL), was mainly devoted to traditional dowel connections, with the special emphasis on large relative rotations of beams and columns in order to define the amount of strength deterioration comparing to the response at smaller relative rotations. The influence of the number of dowels, their distance from the edges of columns and beams as well as the amount of the confinement around the dowel was investigated. These experimental studies are overviewed in Section 2, while the main results are summarized in Section 3.

Since the knowledge about the seismic response of dowel connections in precast structures was quite limited, the adequate numerical models were almost not available. Using the results of experiments these models were identified. For this purpose, quite robust hysteretic macro-model, which is included in the open-source research based OpenSees programme platform (Mazzoni, 2009) as well as in the commercial programme SAP 2000 (Computers and Structures, 2011), was efficiently applied. This model is briefly described in Section 4.1, and its efficiency is demonstrated in Section 4.2, where the analytical results are compared with the cyclic responses recorded during the experiments.

2. THE OVERVIEW OF THE EXPERIMENTS

2.1. Objectives

Prior to the research, performed within the SAFECAST project, the cyclic response of dowel connections was investigated by several researchers (Dulacska, 1972, Mills, 1975, Vintzeleou and Tassios, 1987). Based on these researches the formula, which can be used to estimate the strength of the dowel under the monotonic load, was proposed:

$$R_u = 1.3\phi^2\sqrt{f_c \cdot f_s} \tag{2.1}$$

where R_u is the strength of the dowel, ϕ is its diameter, and f_c and f_s are the strength of the concrete and the steel (of the dowel), respectively. The cyclic strength is 50% – 60 % of the value R_u.

The formula 2.1 was tested mostly on simple units, taking into account only relative shear displacement between the connected elements. Furthermore, the connected elements were mostly pure concrete blocks without any longitudinal and transverse reinforcement. Since in the real precast buildings large relative rotations between connected elements are expected and the reinforcement, particularly the transverse one, can influence the response and the type of the failure of the connection, a set of 13 experiments simulating these "real conditions" was performed. For this purpose full-scale specimens were designed according to the Slovenian (Eurocode) practice (see the next subsection).

The main idea and the main goal of these experiments are outlined in Figure 2.1. In the ideal case the plan was to obtain the following sequence of the behaviour: (1) the strength of the connection at small rotations (R_{u1}) is large enough to enable yielding of the column; (2) due to the large relative rotations the strength of the connection deteriorates (R_{u2}) more than the strength of the column – consequently leading to the failure of the connection prior to the failure of the column.

To achieve large rotations, the column should be flexible enough and at the same time strong enough to withstand the force transmitted through the connection. It was very difficult to achieve the proper balance between these two requirements. Several test setups (including steel elements) were studied with limited success. At the end it was decided to use specimens with RC columns. The cross-section dimensions were chosen to provide suitable flexibility and the variation of the amount of column reinforcement provided adequate strength of columns.

While the strength of the columns was possible to estimate with reasonable accuracy, the estimation of the strength of the dowel using formula 2.1 was more inaccurate. Therefore, the dimensions and reinforcement of columns was varied in order to define the most suitable combination of the strength of dowel and the column. Prior to the cyclic tests, monotonic tests were also preformed in order to obtain more precise data about the strength of the dowel.

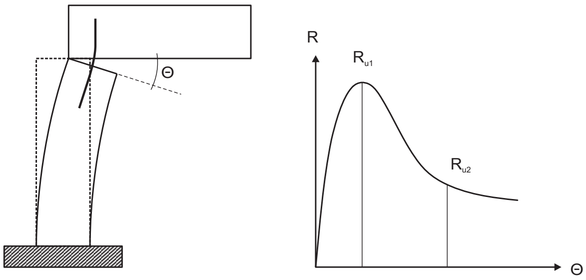


Figure 2.1. Expected behaviour of the connection

2.2. Overview of the Experiments

Several types of dowel connections were investigated in order to define the main parameters that influence the failure of this traditional beam to column connections. All investigated connections are typical for the precast practice in Slovenia and neighbouring countries. The typical setup of the experiment is presented in Figure 2.2.

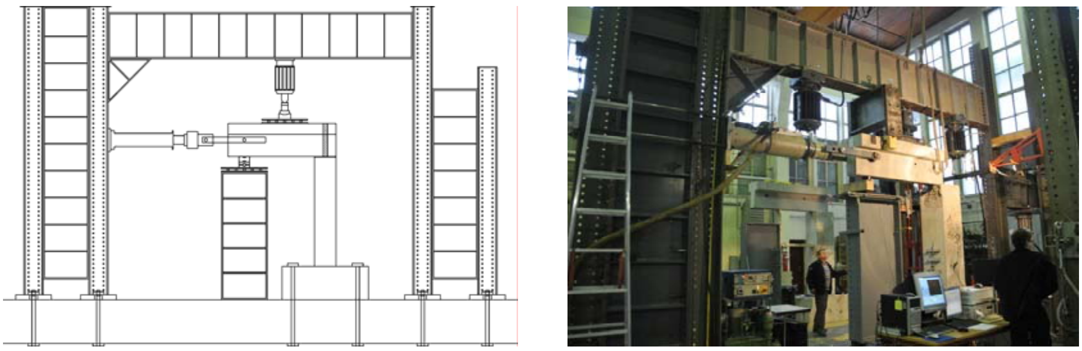


Figure 2.2. Setup of the experiments

The tests of different types of connections, listed below, were performed:

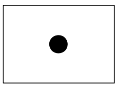
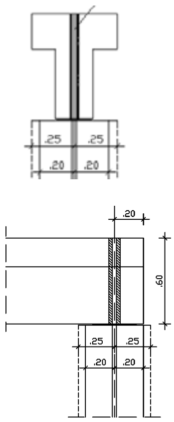
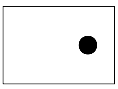
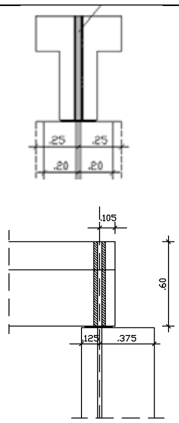
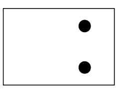
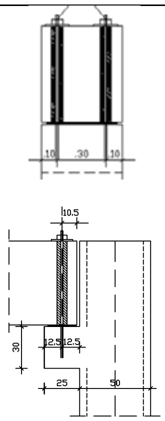
1) *A single dowel of diameter ϕ = 28 mm, located at the centre of column cross-section (see Table 2.1).* This type of connection represents typical roof beam to column external connection. The dowel was located 20 cm or 25 cm (7ϕ or 9ϕ, respectively) from the column edge (depending on the dimensions of the column). The cross-section of tested columns was of the rectangular shape. Their size and reinforcement was varied (see Table 1), depending on the type of the test (small or large relative rotations of beams and columns). Beams had "T" shape cross sections and were the same in all tests.

2) *A single dowel of diameter ϕ = 28 mm located eccentrically in the column cross-section (see Table 2.1).* This is typical for roof beam to column internal connections. The dowel was located 12.5

cm from the column edge (4.5ϕ). Like in the previous type of connection, the dimensions and reinforcement of columns were varied, while the “T” shape beams were the same in all tests.

3) *Two dowels of diameter ϕ = 25 mm, placed eccentrically near the edge of the column corbel.* This is typical for intermediate story beam to column connections (Table 2.1). Dowels were located 12,5 cm (5ϕ) from the edge of the corbel. As in the previous tests the columns were rectangular. The shape of the beams was changed, and the rectangular beams were investigated.

Table 2.1. An overview of the experiments

Type of the connection: Plan view (scheme)	Type of the connection: Cross-section	Type of the test	Dowel(s)	Dimensions of the column cross-section	Longitudinal column reinforcement
		Monotonic	1ϕ28	50 cm x 50 cm	16 ϕ 22
				40 cm x 40 cm	8 ϕ 14
		Cyclic – small rotations		50 cm x 50 cm	16 ϕ 22
		Cyclic – large rotations		40 cm x 40 cm	8 ϕ 12
					8 ϕ 14
					8 ϕ 16
					8 ϕ 20
					4 ϕ 18 + 4 ϕ20
		Monotonic	1ϕ28	50 cm x 50 cm	14 ϕ 22
		Cyclic – small rotations			14 ϕ 22
		Cyclic – small rotations	2ϕ25	50 cm x 50 cm	14 ϕ 22
					14 ϕ 22
		Cyclic – large rotations		40 cm x 50 cm	6 ϕ 18 + 2 ϕ14

3. MAIN RESULTS OF THE EXPERIMENTS

3.1. Overview of the Cyclic Response and the Types of the Failure

Two types of beam to column connection failure were observed during the cyclic tests: 1) the failure of the dowel itself combined by the crushing failure of the surrounding concrete and 2) the failure of the beam-column joint, due to the insufficient tension capacity of the concrete and stirrups surrounding the dowel. The type of the failure and the strength strongly depended on the distance of the dowel from the edge of the column or beam, on the amount of provided stirrups in beams and columns as well as on the maximum value of achieved relative rotations between beams and columns.

3.1.1. Dowel failure and crushing of the surrounding concrete - single centrically located dowel

The rupture of the dowel and crushing of the surrounding concrete occurred in all specimens, where the dowel was located relatively far from the edges of the tied beam and column. For example, this type of failure occurred in all tests where the dowel was positioned centrically regarding the column cross-section (see Figure 3.1.a). Typical cyclic response of such connection corresponding to small relative rotations between the beam and column is presented in Figure 3.1.b.

a) specimen after the experiment

b) force – displacement relationship

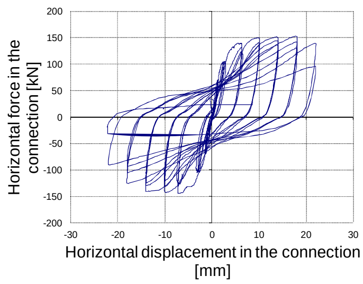


Figure 3.1. Response of single centrically located dowel – SMALL relative rotations of beams and columns

a) specimen during the experiment

b) force – displacement relationship

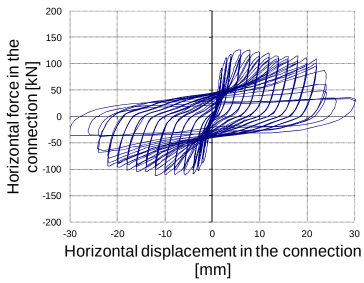


Figure 3.2. Response of single centrically located dowel – LARGE relative rotations of beams and columns

The response was qualitatively the same, when the same type of connection was subjected to large relative rotations between beams and columns (see Figure 3.2.a). Again, failure occurred due to the rupture of the dowel and crushing of the surrounding concrete. However, the strength of the connection was reduced for about 20% (see Figure 3.2.b). In both types of experiments (small and large relative rotations) the dowel in some specimens was ruptured twice, once in a part embedded in column and once in a beam.

3.1.2. Failure of the beam-column joint - single or double eccentrically located dowel

When the dowel was displaced closer to the column edge the type of failure was changed. The beam and column failed due to the insufficient tension capacity of concrete and stirrups that surrounded the dowel (see Figure 3.3.a). The strength of the connection (see Figure 3.3.b) was substantially reduced (to about 60%) comparing to the centrically positioned dowel subjected to small relative rotations of beams and columns. The reduction of the maximum horizontal displacement of the connection was also large. It was reduced to about 30% of the horizontal displacement reached in one centrically positioned dowel.

Hysteretic loop was somewhat asymmetric indicating that the strength of the connection depended on the direction of the loading. The strength was smaller when the connection was loaded in the direction presented in Figure 3.3.a. The direction of the load influenced the strength because the thickness of the concrete cover (distance of the dowel to the edge of the column – see Table 2.1 for more details) was different. In the critical loading direction the thickness of the cover was 12.5 cm, comparing to 37.5 cm, which corresponded to the opposite loading direction.

a) specimen after the experiment b) force – displacement relationship

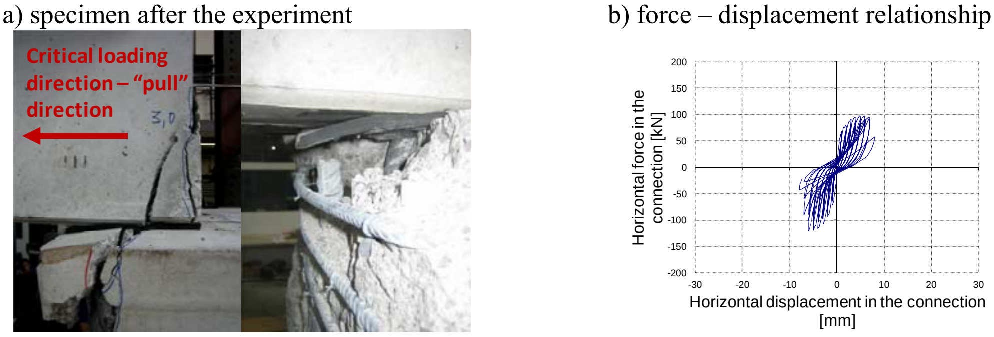


Figure 3.3. Response of single eccentrically located dowel

The similar type of failure was observed in beams and columns, which were connected using two eccentrically positioned dowels (Figure 3.4.). However, the displacement capacity was considerably improved. The reasons are two: 1) The relative thickness of the concrete cover in the critical direction was slightly larger - 5 times the diameter of the dowels, and 2) The dowels were located close to the column corners, where the effectiveness of the stirrups was better. In this type of the connection the substantial damage of beams and columns was followed by the rupture of the dowel.

a) specimen during and after the experiment b) force – displacement relationship

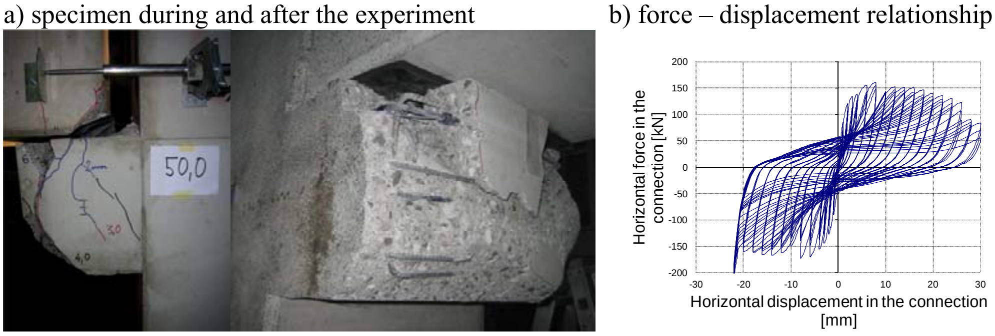


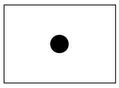
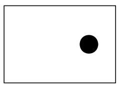
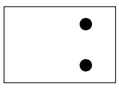
Figure 3.4. Response of two eccentrically located dowels

3.1. Summary of the Main Experimental Results

The main results of the experiments, the strength of the connection and the type of the failure, are summarized in Table 3.1. For each connection two values of measured strength, corresponding to different loading directions, are presented. Strengths, which were estimated using formula 2.1, are presented in parentheses. Smaller value in parentheses corresponds to the measured material properties. The larger values were obtained taking into account increased strength of the confined concrete (due to the stirrups) and strain hardening of steel.

Formula 2.1 can be used to predict the strength of the dowel itself, and is not suitable when the other types of failure are expected. There are several other formulas (e.g. Vintzeleou and Tassios, 1987; CEN/TC 250, 2009), which were proposed to estimate other types of the connection failure, however since they in the majority of cases considerably underestimate the strength, they are not presented in the paper. The main deficiency of these formulas is that they do not include the influence of the strength of the stirrups in column and beam to the strength of the connection. In Table 3.1 all values that do not correspond to the strength of dowel itself are presented in italic and marked red.

Table 3.1. Summary of the strengths of the connections and their type of failure: experimental versus (analytical) values

Type of the connection	Type of the test	Small rotations	Large rotations	Type of failure
	Monotonic	260/204 kN (176 kN; 218 kN)*		Dowel
	Cyclic	153/145 kN (98 kN; 123 kN)*	127/116 kN (84 kN; 108 kN)*	Dowel
	Monotonic	_97kN_**/248 kN (169 kN; 211 kN)*		Joint
	Cyclic	_97kN_**/120 kN (101 kN; 126 kN)*		Joint
	Cyclic	_157kN_**/250 kN (161 kN; 201 kN)*	> _100kN_**/112 kN (135kN; 180 kN)*	Joint and Dowel (small rotations) Column (large rotations)

* Values in parentheses represent the strengths, which were estimated using formula 2.1 (smaller values correspond to measured material properties, larger values were obtained taking into account increased material properties due to the confinement of concrete and steel strain hardening).

** Red italic values represent the strengths, which correspond to the failure of the beam-column joint due to the insufficient tensile strength of concrete and stirrups, and therefore cannot be estimated using formula 2.1 (these values cannot be compared with strengths presented in parentheses)

It is evident from the Table 3.1 that formula 2.1 in the majority of cases underestimates the actual strength, even if the increased material properties (confinement of the concrete and strain hardening of steel) are taken into account. Presented experiments proved that the strength of the dowel subjected to the cyclic load is 50 – 60 % of that corresponding to the monotonic load.

In cases where the beam and column failure is expected the amount of the stirrups around the dowel(s) is particularly important, since it substantially influence the strength of the connection, preventing the failure of the concrete core. In general quite large amount of stirrups is recommended (mechanical volumetric ratio of about 0,2) in the critical regions of columns and beams near their connections.

4. MACRO NUMERICAL MODEL OF DOWEL CONNECTIONS

For the practical assessment of the complex response of connections in precast buildings, robust and efficient (macro) models are needed, which provide proper balance between the reliability and the amount of work needed in the analyses. To fulfil this goal, quite robust macro “hysteretic” model (Dowel, 1998) was selected among several other possibilities. It was chosen taking into account that it is (similar versions) already included in the open source research program platform OpenSees (Mazzoni, 2009) as well as in some commercial programmes as SAP 2000 (Computers and Structures, 2011). In the paper the version of the model included in the SAP 2000 is briefly described in Section

4.1, while the efficiency of this model is demonstrated in Section 4.2 where the analytical results are compared with the experimentally registered cyclic response.

4.1 Short Description of the Numerical Model

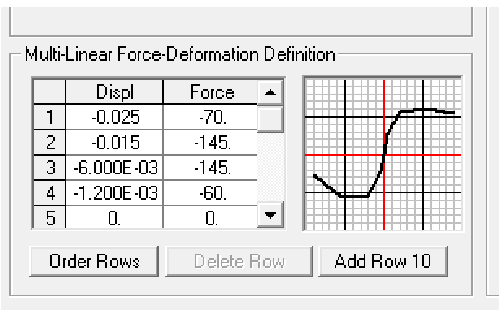
To model experimentally tested connections in programme SAP 2000, an uniaxial Link element of "Multilinear Plastic Nonlinear" type was used. Among three available hysteresis types, the "Pivot" was found the most appropriate.

The selected element is capable to describe quite versatile response envelopes as well as to regulate the amount of pinching and unloading stiffness of the hysteretic loops. It was used for modelling connections of very different types. In the paper its efficiency is demonstrated on the examples of dowel connections, only. The detailed theoretical background of the element can be found elsewhere (Dowel, 1998). Here only the main features are summarized.

The response envelope is defined by the unlimited number of Force-Displacement pairs (see Figure 4.1.a). Beside these data, three types of coefficients, denoted in SAP 2000 as α, β and η should be also determined. These parameters are used to control the cyclic response.

Parameters α (α_1 and α_2) define the primary pivot points, which control the unloading stiffness (see Figure 4.1.b). Technically speaking, pivot points are defined multiplying the values of forces, corresponding to the first characteristic points on the envelope, by the parameters α (see Figure 4.1.b). To obtain the large unloading stiffness, the large values of α should be chosen. For most of the analyzed connections, the unloading stiffness was very large; therefore in the majority of cases the value of 10^4 was used for α. To obtain the so-called "origin-oriented" hysteretic loop, the α factors should be 0.

a) multi-point envelope



b) Parameters and characteristic points of the model

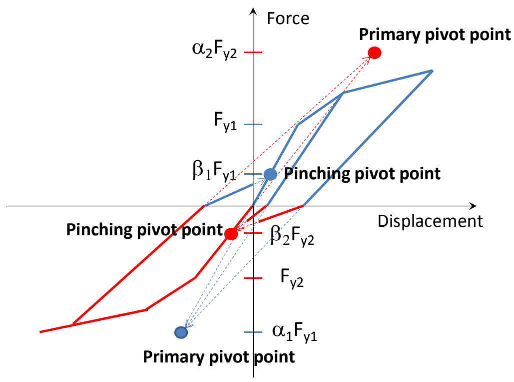


Figure 4.1. "Hysteretic" macro model

Parameters β (β_1 and β_2) define the pinching pivot points (see Figure 4.1.b). They are determined multiplying the values of forces and displacements corresponding to the first characteristic points on the envelope, by parameters β. For larger β parameters smaller pinching of hysteretic loop is obtained. It is not only the β parameter, which controls pinching. The pinching also strongly depends on the first characteristic points of the envelope.

The parameter η is intended to define the strength and stiffness degradation. However, due to certain bugs in the programme, it was ignored, and did not have any influence to the presented study.

4.2 Comparison of the Analytical and Experimental Results

In spite of considerable diversity of the response of analyzed connections, the "Hysteretic" model was capable to model the cyclic response for all of them with reasonable accuracy. The match with the experiment depended on the type of the connections, but was in general quite good. Some typical examples of the response and comparison with the experimental values are presented in Figure 4.2.

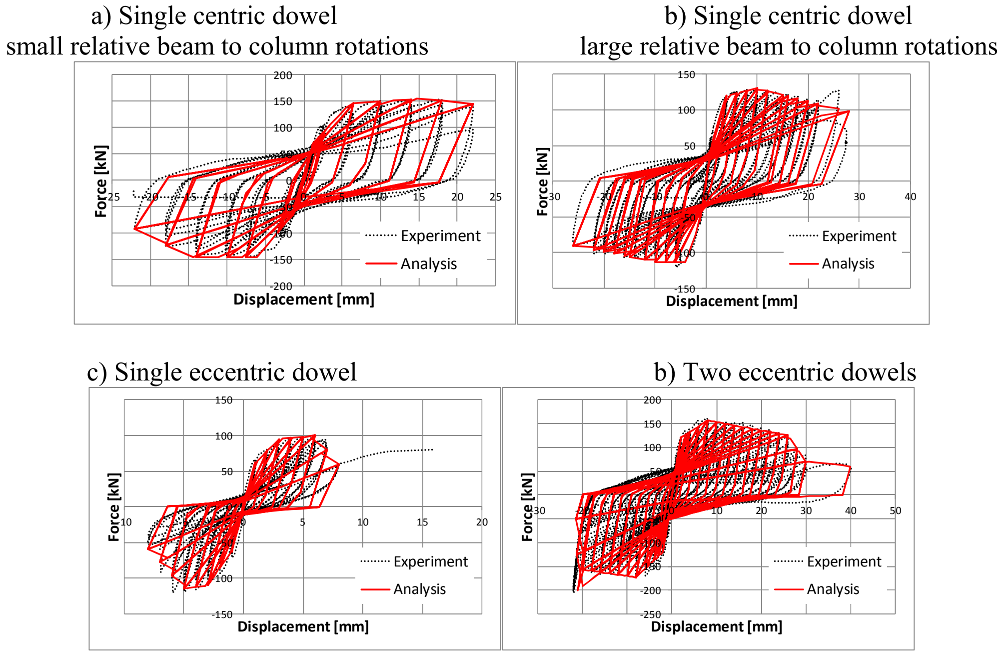


Figure 4.2. Comparison of the analytical and experimental results

For each type of the connection the input parameters were defined, based on the corresponding experiment. The input parameters were varied in the range listed below:

- Single centric dowel: α_1 and $\alpha_2 = 10^4$, β_1 and $\beta_2 = 0.55 – 1.0$
- Single eccentric dowel: α_1 and $\alpha_2 = 10^4$, β_1 and $\beta_2 = 0.2$
- Two eccentric dowels: $\alpha_1 = 15$ or 10^4 and $\alpha_2 = 5$ or 104, β_1 and $\beta_2 = 0.45 – 0.6$

The used model successfully simulated almost symmetric as well as an asymmetric cyclic response. Its great versatility was demonstrated when it was successfully used to model the response of connections with good energy dissipation capabilities as well as those were the hysteretic pinching was more pronounced.

In spite of the great versatility, some deficiencies of the element were also identified. It was not able to simulate the strength and stiffness degradation within the repeated cycles of the same amplitudes. Since the parameter, which is intended to regulate this degradation (η), is available in the input data, this feature might be available in the future versions of the programme.

In some connections (e.g. single centric dowels) the amount of pinching of single hysteretic cycles was variable, and depended on the displacement amplitude. This was not able to simulate with the chosen model, therefore it was calibrated considering larger cycles. It is important to mention, that although the modelling of the smaller cycles was less accurate, this had no significant influence to the overall response. The hysteretic model neither can describe the curved shape of the hysteretic loops at the unloading phase; however, this was also irrelevant for the overall response.

5. CONCLUSIONS

The experimental investigations of typical dowel beam to column connections were performed as a support of the FP7 SAFECAST project, where one of the main goals was to define design procedures for different types of innovative and traditional connections, which were predominantly designed by engineering feeling. In the paper, a set of cyclic and some control monotonic tests of dowel beam to column connections are presented.

Two types of failure of the investigated connections were identified: a) the rupture of the dowel and crushing of the surrounding concrete and b) the failure of the beam to column joint due to the insufficient tension strength of concrete and stirrups surrounding the dowel. The type of the failure and strength of the connections strongly depended on: a) the distance of the dowel from the edge of the column and beam, b) the amount of the provided stirrups in beam and column, and c) the amount of relative rotations between column and beam. The influence of the large relative rotations between column and beams (typical for precast buildings) to the strength of their connections has never been tested before. Due to the large relative rotations, the 20% reduction of the strength of the connections was identified. In asymmetric connections the strength was also influenced by the direction of the loading, since the distance of the dowel from the edges of column and beam was different.

It has been confirmed that the cyclic strength of the connections was 50 – 60% of the strength measured during the monotonic tests (as it was noticed in the previous researches). In the majority of cases, the existing formulas, which can be used to estimate the strength of the dowel itself, underestimated the actual strength. The difference between the predicted and actual strength was even larger in the case of other types of failure.

To define the appropriate design procedures for the connections an appropriate numerical model was needed, which would be able to provide proper balance between the reliability and the amount of work needed in the analyses. Based on the experimental results, a quite robust numerical non-linear “Hysteretic” macro-model of these connections has been defined and successfully used to model very different types of connections. In the paper its use is demonstrated on the example of traditional dowel connections.

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