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Experimental and Numerical Analysis for the Purpose of Inter-Module Connection Response Validation

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Abstract

This paper discusses problems related to mechanical behaviour of inter-module connections in modular buildings. A specific solution is analysed here. The aim is to collect data about the response of a newly developed inter-module connector and also to create a valid computational model of this structure. Experimental tests are done on medium-scale specimens made of concrete and the connector. A novel test stand has been devised for this purpose and is shown. Digital Image Correlation is involved to study development of cracks observed during the tests. This is followed by numerical static analysis. Appropriate finite element model, enabling description of the nonlinear response of the structure with cracking is searched for with the aid of model updating process. The final model resembles the whole test stand and involves nonlinear concrete damage plasticity material law. Good correlation between the experiments and the numerical estimations is achieved. Thus, the behaviour of the inter-module connection is well determined, while the developed model can be used to analyse the response of a single unit or the whole modular building

Keywords: inter-module connection, experiments, validation, digital image correlation, model updating, finite element method, nonlinear static analysis, concrete damage plasticity.

1 Introduction

Modular buildings become more and more popular. These precasted structures are made of standardized units, with load bearing elements build of steel, concrete or wood. They are produced and assembled quickly and with high quality. Application of prefabricated modules in the field of design and construction of buildings opens up a lot of possibilities regarding arrangement and configuration of the structure. Thus, even specific requirements or demands on the building performance or architectural characteristics and properties can be relatively easily met with aid of this technology. Moreover, they are social and environmental friendly and sustainable. For example the amount of time required to assemble a modular building compared to construction time of a classical concrete or steel building is significantly smaller, so disturbances and the impact of construction works on the surroundings, especially in crowded city centres, are strongly reduced. The modular buildings can be also easily disassembled and reused in different locations (see [1][2]). That is why they may be treated as the future of modern housing industry.

Modular buildings and the traditional ones are generally built from the same materials, designed using the same codes and with aid of matching architectural specifications. Thus, the problems related to ultimate limit and serviceability limit states of the buildings need to be solved, as usual. One of the issues to be addressed by Researchers is appropriate connection between the modular units. Different options are available, like splice shoes, alveolar joint, tenons or other inter-module connections. The key aspect here is of course load bearing capacity, easy installation, reliability and cost-efficiency of such system. Some interesting solutions have been already tested, but new, even better developments are still searched for. Efforts are also done to validate approach to numerical modelling of inter-module connections, which will allow to facilitate and ease the process of detailed design of such element. Some interesting examples of recent work in this field can be found in [3]-[12].

In this article, we focus our attention on experimental and numerical analysis of a specific inter-module connection response. Validation of the computational model is the most important aspect here. Once the model is validated it can be then used to analyse mechanical behaviour of a single unit or the whole modular building.

2 Methods

In order to perform validation of the approach to numerical modelling a comprehensive test program is launched. It includes: experimental tests, measurements, data acquisition and post-processing of the collected information, as well as static nonlinear Finite Element Method (FEM) analyses and comparisons of the measured and estimated responses.

The analysed inter-module connection is made of steel gusset plates and steel reinforcing bars which are welded together. The connector is attached to a concrete modular unit at the unit corners, during the concrete pouring. A composite action keeps it in position when the concrete is dry and mature.

In view of that, medium-scale test specimens were produced in the form of a concrete cantilever with built-in inter-module connector. The idea was to cause debonding between the connector and the concrete, which may be problematic. A novel test stand was developed. It maintained its equilibrium during the test, without any excessive supports, and allowed to easily resemble the cantilever bending of the specimen with the aid of a standard testing machine. 3 specimens were manually built at the Gdańsk University of Technology, as shown in Figure 1. They were painted white to ease the process of concrete cracks detection. The specimens were attached to a steel frame by the connector and using bolts. Then the research object was put between a hinged moving plate and a roller support, as presented in Figure 2 and Figure 3, using a small a manual crane lift. The load was applied through the hinged plate with the aid of a testing machine. The tests were done at the testing machine cross-head speed of 2mm/min to the moment of failure. During the experiments the force applied by the machine was registered, vertical and lateral displacements of the specimens were measured with the aid of HBM sensors and photogrammetric documentation of the side surfaces of the specimen was created using Canon 5d Mark III with EF 50mm, f/1.8 lens (refer to Figure 2 and Figure 3). The photos taken during the tests were post-processed using Digital Image Correlation (DIC) in the ARAMIS Professional software. In effect, strain contour plots were creating allowing for easy detection of cracks, that had been developing during the experiments.

a) b)

Figure 1: The specimen with the inter-module connector produced at the Gdańsk University of Technology: a) concrete pouring, b) cured and ready for tests.

a) b)

Figure 2: The experimental test stand: a) side view, b) front view.

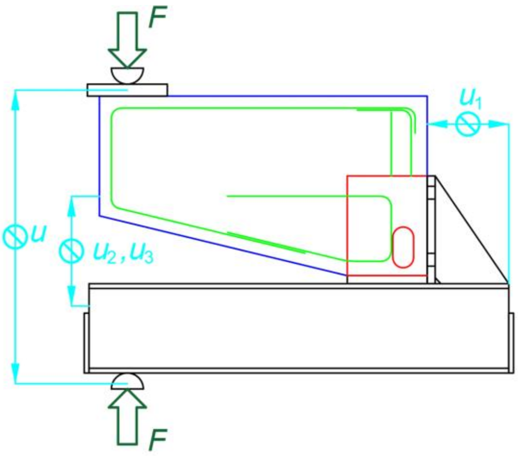


Figure 3: The testing scheme and location of displacement sensors (blue colour – external contour of the specimen, red colour – contour of the connector, green colour – reinforcement).

Computational simulations are now an important part of structural design process. Nevertheless, the methods and approaches used to create a numerical model have to be validated to assure their reliability, especially, when new solutions are proposed, which is the case here. Therefore, a detailed model of the test stand was created in the Finite Element Method (refer to [13]) environment using Abaqus and an attempt was made to appropriately estimate the response of the specimen and the inter-module connector. Different versions of the model were analyzed and studied. The model updating process became quite important. Finally, the one shown in Figure 4 with the assigned boundary and contact properties was developed.

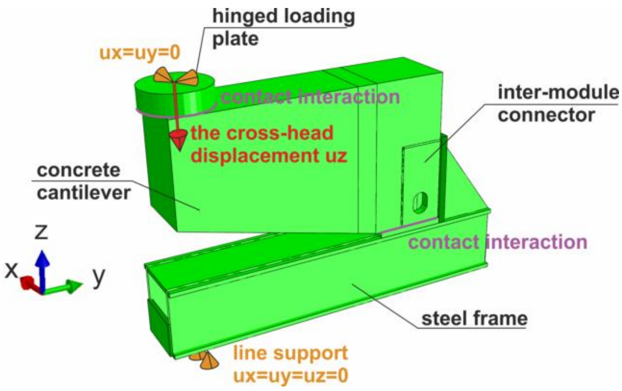
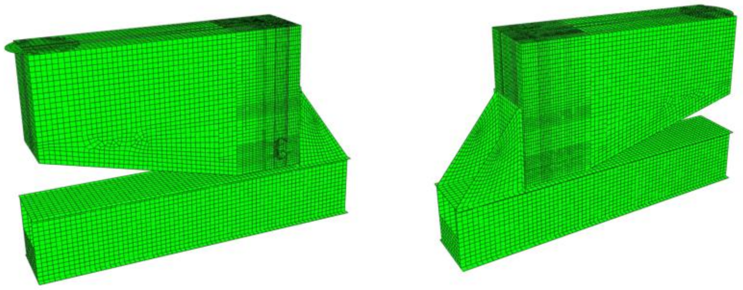


Figure 4: The model of the cantilever with boundary, contact and loading properties.

In the model solid elements (C3D8) were used to recreate concrete parts and the steel connector, shell elements (S4) were employed to simulate the response of the supporting steel frame, while the reinforcement was built of truss elements (T3D2). A mesh independence study (h-refinement) has been performed to provide reliability of the results. The mesh is presented in Figure 5.



a) b)

Figure 5: The mesh: a) specimen left side, b) specimen right side.

Appropriate choice of constitutive laws describing stress-strain relations of the used materials was also important issue during the model updating process. The attention was mainly focused on the behaviour of concrete. Here, the concrete damage plasticity (CDP) law was used, because it enables efficient simulation of the crack propagation process, see for example [14][15][16].

The Newton's-Raphson method has been applied to solve the nonlinear equilibrium equations of the static problem. Apart from material and contact nonlinearities, which have been mentioned earlier, also the geometric one is involved.

3 Results and discussion

In this chapter the experimental measurements and FEM estimations are compared. The computational results are presented for the final version of the model, as described in chapter 2. It is important to mention, that during the model updating process the attention was focused on the appropriate choice of the material laws constants, properties and stiffness of the connection between the specimen and the steel frame, as well as on the contact interaction descriptions. In Figure 6, Figure 7 and Figure 8 displacements measured during the experiments are compared with FEM estimations, correspondingly in *u*, *u1*, *u2* and *u3* locations.

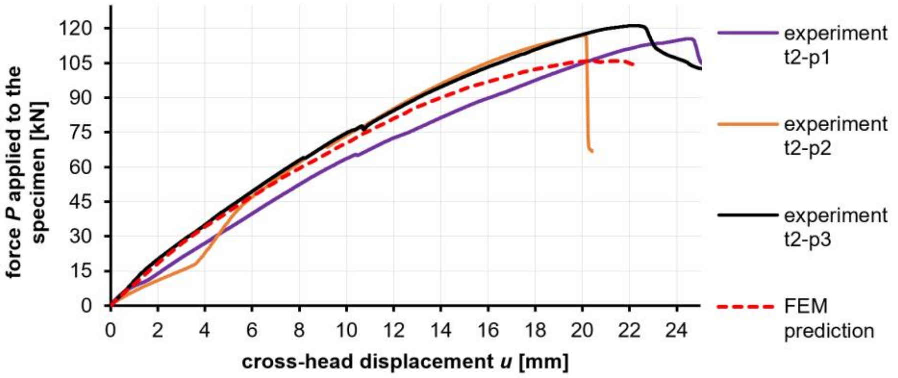


Figure 6: Comparison of the experimental and FEM displacement results in the *u* location (shown in Figure 3).

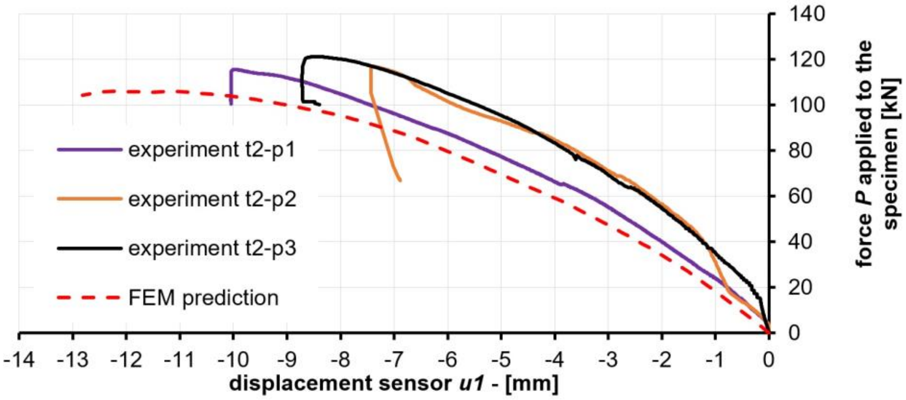


Figure 7: Comparison of the experimental and FEM displacement results in the *u1* location (shown in Figure 3).

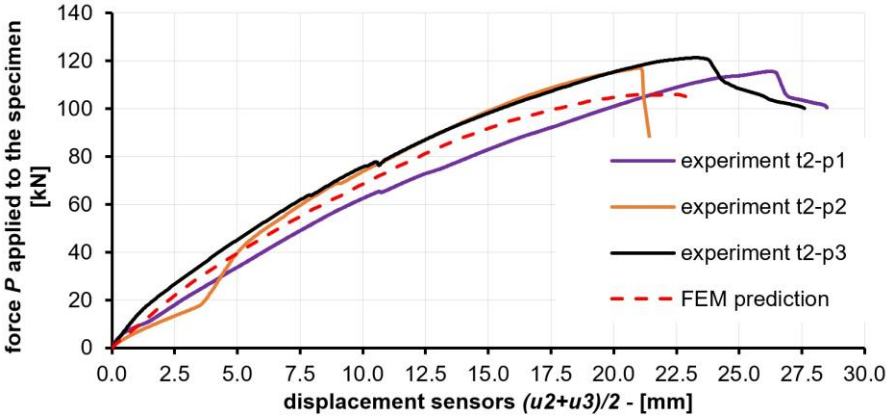
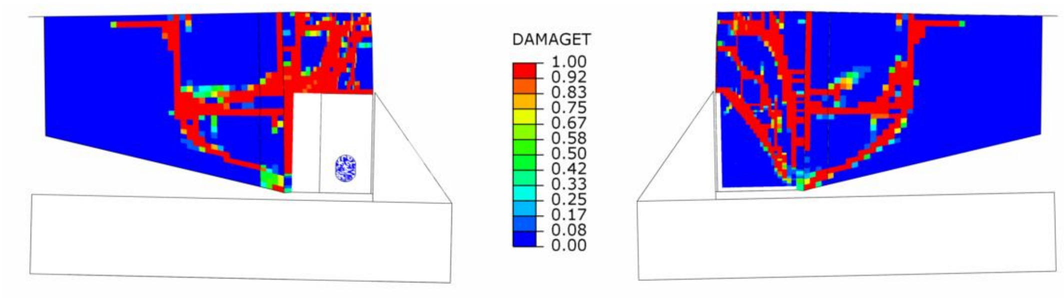


Figure 8: Comparison of the experimental and FEM displacement results in the *u2* and *u3* location (both shown in Figure 3).

The displacements predicted by the FEM model in the locations, where the measurements were done, correspond qualitatively and quantitatively with the experiment, hence the accuracy of the model in this respect is very good. The specimen failure in the computations is observed, when the *P* force equals approximately to 110kN, whereas the maximum force that could have been transferred during the laboratory experiments ranges from 115kN to 121kN (mean value is 118kN). Therefore, the relative error between the failure force estimation and the measured value is approximately 7%, which we find to be low.

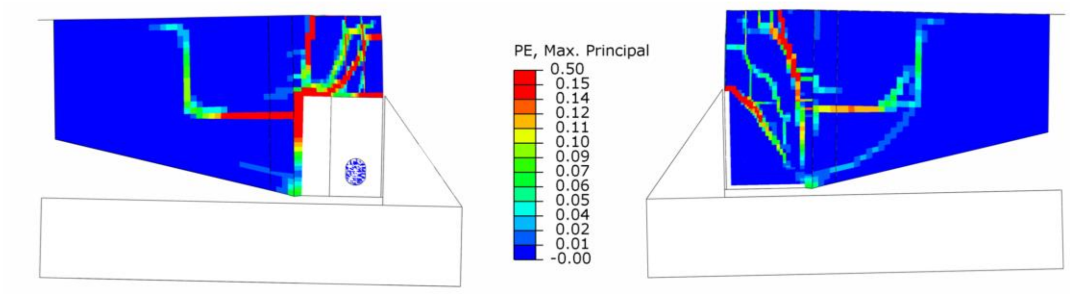
The development of cracks is also studied. The static analysis suggest, that when the cantilever reaches the maximum possible *P* force level, numerous damages should be visible, which subsequently lead to final failure. These should appear along the external edges of the inter-module connector. Some cracks should propagate vertically above the cantilever supporting edge and above the oval-shaped hole in the connector.

Moreover, strong inclined damage above and within the inter-module connection should develop together with inclined cracking running between the cantilever external supporting line and the loading hinged plate. The development of cracks in the model is presented with the aid of the nondimensional tensile damage variable DAMAGET (ranging from 0 - undamaged to 1 - fully damaged material in tension) and equivalent plastic strain in uniaxial tension, denoted as PEEQT. It is common to use these parameters, when crack propagation process is analyzed (refer to for example [14][15][16]). Quilt contour plots of DAMAGET and PEEQT taken at the moment when the specimen failed in the FEM analysis are shown, correspondingly in Figure 9 and Figure 10. These are compared with the photogrammetric documentation and DIC images, that are presented in Figure 11 and Figure 12.



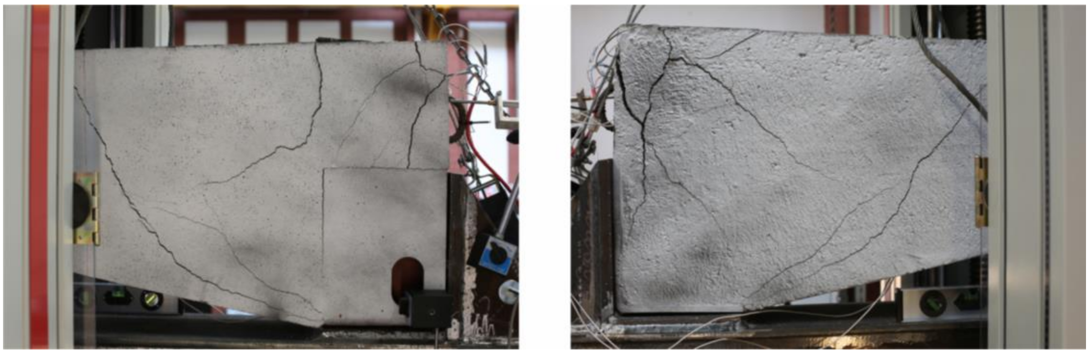
a) b)

Figure 9: DAMAGET contours on the external sides of the specimen in FEM analysis when it failed: a) left side, b) right side.



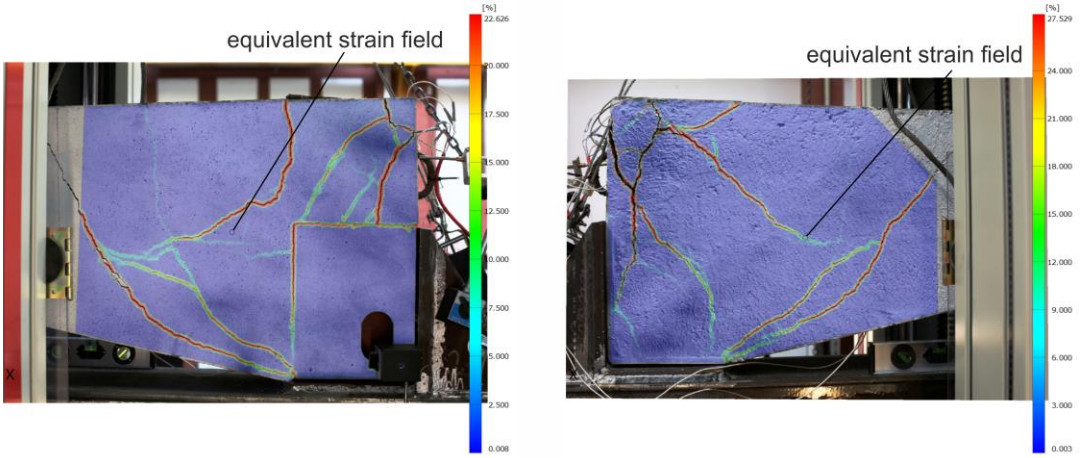
a) b)

Figure 10: PEEQT contours on the external sides of the specimen in FEM analysis when it failed: a) left side, b) right side.



a) b)

Figure 11: Photos of the failed specimen: a) left side, b) right side.



a) b)

Figure 12: DIC images of equivalent strain created using ARAMIS: a)left side of the specimen, b) right side of the specimen.

The comparisons reveal that the computational model is also capable of reasonably appropriate predictions of crack development observed during the experiment. Moreover, the experiments allowed to simulate debonding of concrete from the connector, which may be a potential failure mechanism.

In the light of the above it can be stated that the computational FEM model has been successfully validated and therefore can be used in further analyses of the inter-module connection, especially including simulations of a single unit or modular building.

4 Conclusions and Contributions

In this paper a specific inter-module connection was analysed in detail. The study was focused on identification and determination of the mechanical response of the connector and its potential failure modes, like for example debonding of the concrete from the connector.

An interesting and novel test stand was proposed to study these problems experimentally. Concrete specimens with attached connectors were subjected to cantilever bending. The stand maintained its equilibrium during the test, without any excessive supports, and allowed to easily resemble the desired state and destroy the specimen with the aid of a typical testing machine.

An attempt to use DIC for the purpose of crack propagation observations was done. It turned out to be efficient and accurate.

It has been shown in the paper that model updating is an important process. Here, it was necessary to apply suitably calibrated material laws, like for example CDP for concrete, select carefully the stiffness of the connection between the specimen and the steel frame, as well as focus some attention on the interaction between the loading plate and the specimen.

In effect it was possible to develop a computational model which provided results, that qualitatively and quantitatively corresponded with the experimental measurement and observations.

It is emphasized that reliability of a numerical model has to be always assured, especially for newly designed solutions.

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