MODERN NUMERICAL MODELING OF REINFORCED CONCRETE STRUCTURES

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Nowadays, many computer software products are available for the numerical modeling of reinforced concrete structures; however, the accuracy of the numerical models created by the programs can only be accepted with a properly developed and verified modeling procedure. Within the framework of the present article, we present the numerical modeling possibilities of reinforced concrete structural elements and their connections through numerical models made by a modeling procedure we have built. In our studies, we also dealt with quasi-static unidirectional (horizontal and vertical) and cyclically variable direction and magnitude loads. The numerical models were created using the ATENA 3D three-dimensional nonlinear finite element software developed specifically for the study of concrete and reinforced concrete structures. In many cases, the results obtained by numerical experiments were compared with the results obtained by laboratory experiments, and some of our numerical experiments were compared with the results obtained using two-dimensional finite element software. Within the framework of this article, we would like to give a comprehensive picture of the numerical studies we have performed. We have also briefly summarized the results and experiences obtained from 3D nonlinear finite element studies.

Keywords: ATENA 3D software, nonlinear finite element analysis, cast-in-situ reinforced concrete structures, prefabricated reinforced concrete structures

1. INTRODUCTION

Nowadays, research engineers perform numerical studies on a number of topics, as a result of which they are able to model the behavior of individual structural elements by computer. At the same time, there is a growing demand for this from practicing engineers. However, in order to verify numerical models and their results, it is essential to perform laboratory experiments by which we can support the correctness and accuracy of our numerical models. From a practical point of view, it is important that the numerical model created follows the real behavior of the structure as closely as possible. Therefore our models will become more and more detailed and thus more complex. From the point of view of modeling reinforced concrete structures, the properties of the materials and material models that can be used in the chosen finite element software cannot be neglected. We must use or apply software with which we can properly study the problem we have analyzed.

In the course of our research, we have dealt with the numerical examination of several reinforced concrete structural elements and are still dealing with them. Our goal is to produce an extensively developed and well-founded numerical modeling technique by the development of numerical models, which we can use to examine reinforced concrete structural elements and their node design in the most appropriate way in reality in the target software. During numerical model development, we perform a significant number of parameter tests, which are basically performed to cover individual structural details, nodes and complete structural elements. Taking advantage of the possibilities provided by the finite element software at the highest level, we performed hundreds of numerical runs through the optimization of the computation time and the finite element distribution through individually parameterizable material models in the software (products).

Within the framework of this article, we present the most important results achieved in the current field of research and in the course of our previous research. A significant part of the results is related to the numerical modeling procedure, but the results obtained by the numerical modeling method are also considered significant research results in the subject. Prior to our research, we conducted a comprehensive literature review, on the basis of which it can be clearly established that the numerical modeling of reinforced concrete structures is basically moving towards high-level finite element calculations. However, the sources available mostly publish laboratory experiments, which were used in only few cases to verify and develop numerical models. Numerical models are almost exclusively 2D linear (Szczecina, Winnicki, 2015, Hwang, Lee, 1999), and less frequently nonlinear (Hawileh, Rahman, Tabatabai, 2010), (Masi, Santeriero, Nigro, 2013); three-dimensional nonlinear finite element calculations are rarely found (Santeriero, Masi 2017), (Arjamadi, Yousefi, 2018). Taking all this into account, there is a growing demand in the subject for the development and application of three-dimensional nonlinear finite element models. High-level numerical studies of reinforced concrete structures, such as the structural elements and their connections discussed in this article, can by no means be considered a fully exploited research area. Understanding the behavior of monolithic and precast reinforced concrete structures and the numerical studies of the different connection designs and the different types of reinforcement placing used in them will help to understand and describe the behavior of the given connection / structural element. Thus, with 3D nonlinear finite element software proven on the basis of real laboratory experiments, a number of structural designs that have not been tested under laboratory conditions or are difficult to handle experimentally due to their size can be examined. Within the framework of this article, we have summarized the results and experiences obtained in our numerical studies. We summarized what results could be achieved by the modeling procedure we developed during the examination of each structural element and connection.

2. DEVELOPMENT OF THE NUMERICAL MODELLING METHOD

The finite element models were built using the ATENA 3D nonlinear finite element software *(Figure 1(a))*. Numerical model development was basically started with the performance of quasi-static studies, and then the results and experiences of quasi-static computation were used in cyclic studies *(Figure 1(b))*. In many cases, a laboratory experiment published in the literature was available. The parameters and results provided in the publications were used in the preparation of the numerical models.

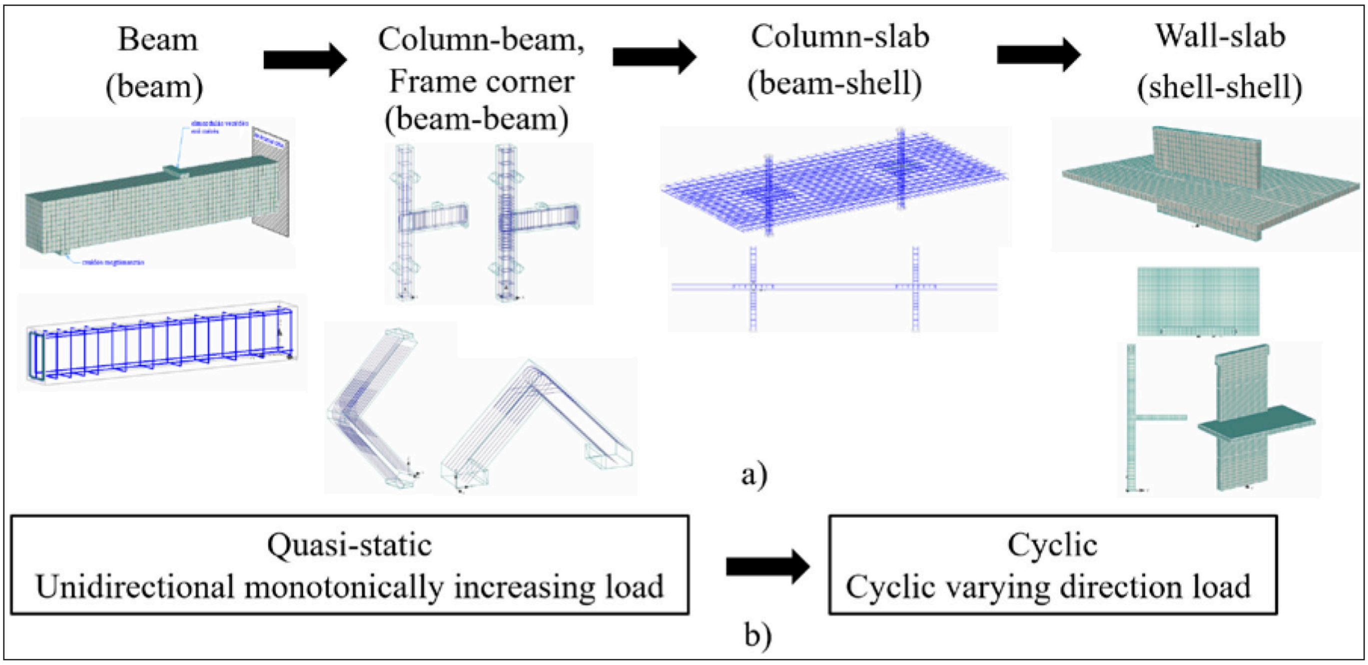
In the quasi-static numerical experiments, the material model of concrete was defined by an individually parametrized model on the basis of our previous results (Haris, Roszevák 2017, Roszevák, Haris, 2019). The reinforcement material model is specified according to the properties of the reinforcement used in the laboratory experiments and it is provided with the real stress-deformation characteristic *(Figure 2(b))*. The strength properties of the concrete and reinforcement bars have been defined according to the laboratory tests.

The relationship between the concrete and reinforcement bars *(Figure 2(d))* was calculated and defined on the basis of the CEB-FIP 1990 Model Code (*fib*-Model Code for Concrete Structures, 2010). The longitudinal bars were modeled with their real geometry and diameter, the stirrups with a closed rectangular shape other than the actual bending shape, but with their real diameter.

In our cyclic test, the material for concrete shown in *Figure 1(a)* was used. The concrete material model includes the following effects of concrete behaviour (Červenka et al., 2014): non-linear behaviour in compression including hardening and softening, reduction of compressive strength after cracking (Van Mier, 1986), fracture of concrete in tension based on nonlinear fracture mechanics (Hordijk, 1991), biaxial strength failure criterion (Kupfer et al.,1969), tension stiffening effect, reduction of shear stiffness after cracking (Kolmar, 1986) and the fixed (Červenka, 1985, Darwin & Pecknold, 1974) and rotated (Vecchio & Collins, 1986, Crisfield & Wills, 1989) crack direction. For tensile (fracture) and compressive (plastic) behavior, the software uses a smeared crack approach in concrete junction with a fracture plastic model. The rotating and fixed crack models can be used in connection with exponential softening and the Rankine tensile failure criterion. ATENA 3D adds a so-called "Unloading Factor" to model concrete behavior under cyclic loading. The "Unloading Factor" controls crack closure stiffness. The factor mainly influences the shape of the hysteresis curve; in our analyses the parameter was set to zero because this value gives the best fit to real behaviour (Červenka et al., 2014). The reinforcement is defined by cyclic properties based on the Menegotto-Pinto model (Menegotto, Pinto, 1973) *(Figure 2(c))*. In the longitudinal bars placed in the concrete elements, the effect of slipping was taken into account. However, we have set the perfect connection for the stirrups. The slip of the reinforcement bars has been taken into account: the relationship between concrete and reinforcement bars is defined by a memory bond parametrized model. We have taken the bond-slip relationship *(Figure 2(e))* in the model according to the CEB-FIP 1990 Model Code. The placing of the bars has been defined in the same way at the quasi-static tests.

For all nonlinear analyses, an iterative method (Newton-Raphson iteration method) was used to perform the iteration process. The Cholesky resolution was used to solve the state equation of the structure. In the numerical models we used

Fig. 1: Development of numerical modeling method (a) Structural elements, (b) Types of loading



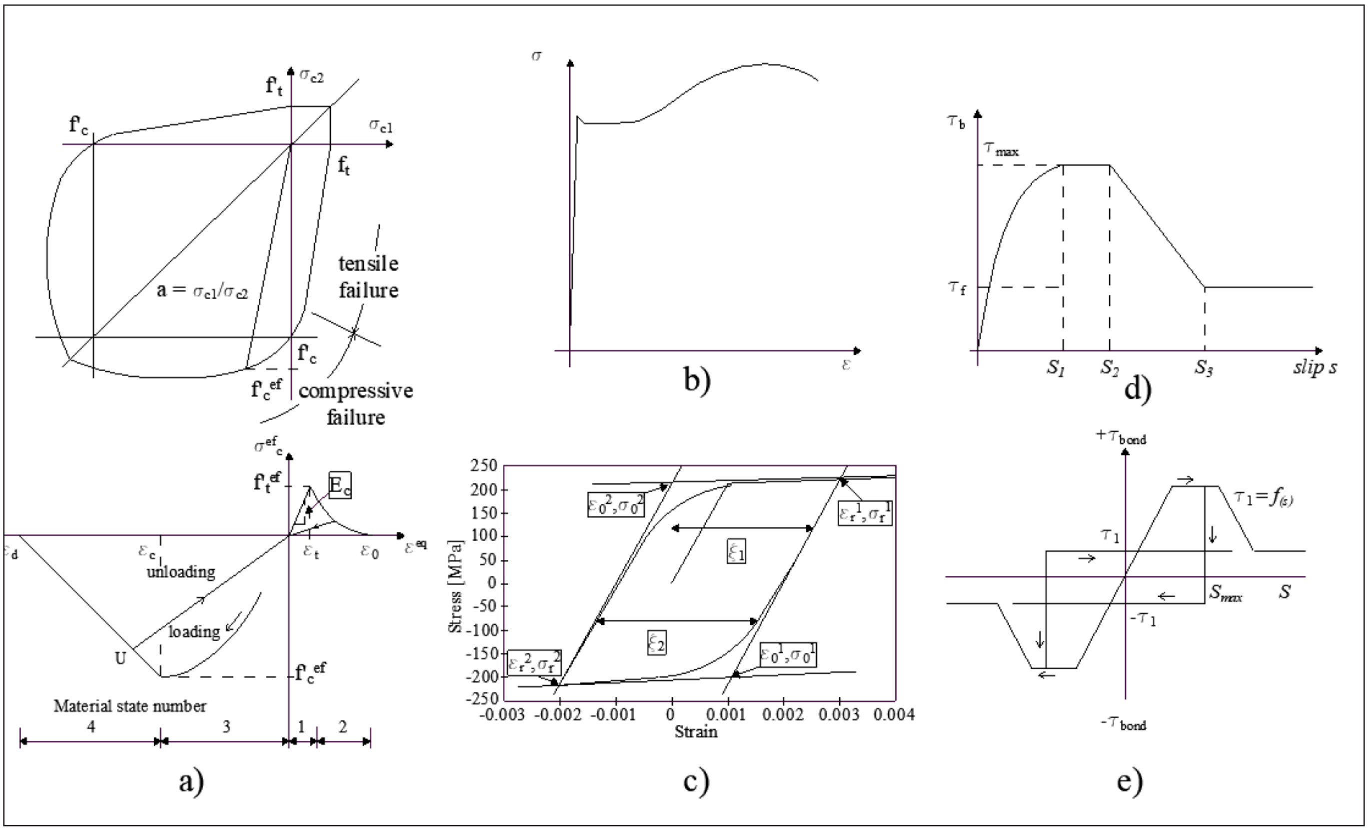


Fig. 2: Material properties: (a) concrete material model, (b) reinforcement stress-strain relationship, (c) cyclic reinforcement model, (d) bond-slip relationship (quasi-static), (e) bond-slip relationship (cyclic). From Cervenka et al., 2014

uniformly quadratic bar functions, and we used 20-node brick elements for the concrete (Haris, Roszevák, 2017). The finite element mesh is distributed uniformly so that there are at least four finite elements within the given cross-sectional dimension (Haris, Roszevák, 2017). The choice of the mesh size of the finite elements depends, in many cases, on the size of the structural element examined and the body elements forming the node model, so in many cases, we used allocated finite elements in the connection environment.

We started our studies with laboratory and numerical experiments of simple reinforced concrete beams in order to be able to verify our numerical model on a simple (single supported) beam element and to examine each input parameter. In the next step, we modeled the beam-beam connection designs, in which the behavior of the closing and opening frame corners and beam-column connections was investigated. Afterwards, we performed the modeling of beam-shell connections, in which we also dealt with the formation of column and slab connections through the determination of substitute equivalent plate width. The final step of the present program is the relationship between shell-shell structural elements. The examination of wall and slab type relationships is an issue which we have already dealt with tangentially before, and we have made preliminary numerical models. The research is currently in the phase of conducting a large-scale, completely novel laboratory experiment of 16 specimens for wall-slab type connections, which can be used for verifying previously developed numerical models, and detailed parameter analysis can be performed.

We have carried out our research in the first place in the field of cast-in-situ reinforced concrete structures; however, the research has reached that stage and we have set up a research group to enable the performance of investigations of prefabricated reinforced concrete structural elements. In the case of prefabricated structural elements, we are currently dealing with the possibilities of modeling the relationships of structural elements and numerical studies of prestressed structural elements.

3. SUMMARY OF RESULTS

Numerical studies of beam-column *(Figure 3(a))* and frame corner *(Figure 3(b))* connections were performed using the 3D modeling procedure we developed for a monotonically increasing, quasi-static load *(Figure 3(c), (d))*. The numerical models were constructed with the actual concrete cross-section and reinforcement used in real international laboratory experiments found in the literature (Yap, Li, 2011; Morgan, 2000), so that the results obtained could be directly compared with each other. In the case of beam-column specimens, a very good agreement can be detected in the initial non-cracked and failure-to-failure sections. With displacement-controlled numerical experiments, the flattening behavioural phase after failure cannot be modeled by the modeling technique we use. In force-controlled numerical experiments, on the other hand, the post-failure behavioural phase can be shown *(Figure 4(a))*. It can be stated that numerical models with actual (real) reinforcement characteristics yield better results than models where the linear elastic-linear hardening reinforcement material model was used. Plastic deformations after failure can be modeled using the real rebar characteristic. The crack pattern produced by numerical tests shows a good agreement with the crack pattern recorded in the laboratory experiments *(Figure 4(b), (d))*.

For a more accurate examination of cracks, reducing the size of the finite element mesh may be a good solution; however, it increases the running time of the models almost exponentially. The "efficiency" of the applied reinforcement placing and rebar quantity can be examined numerically, and in this case the connection can be optimized for load-bearing capacity, deformability, reinforcement quantity and even costs (Roszevák, Haris, 2019). We have shown that it

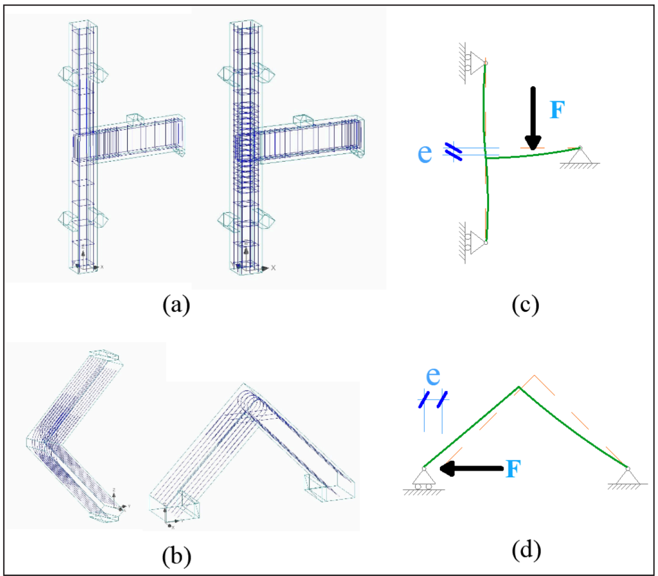


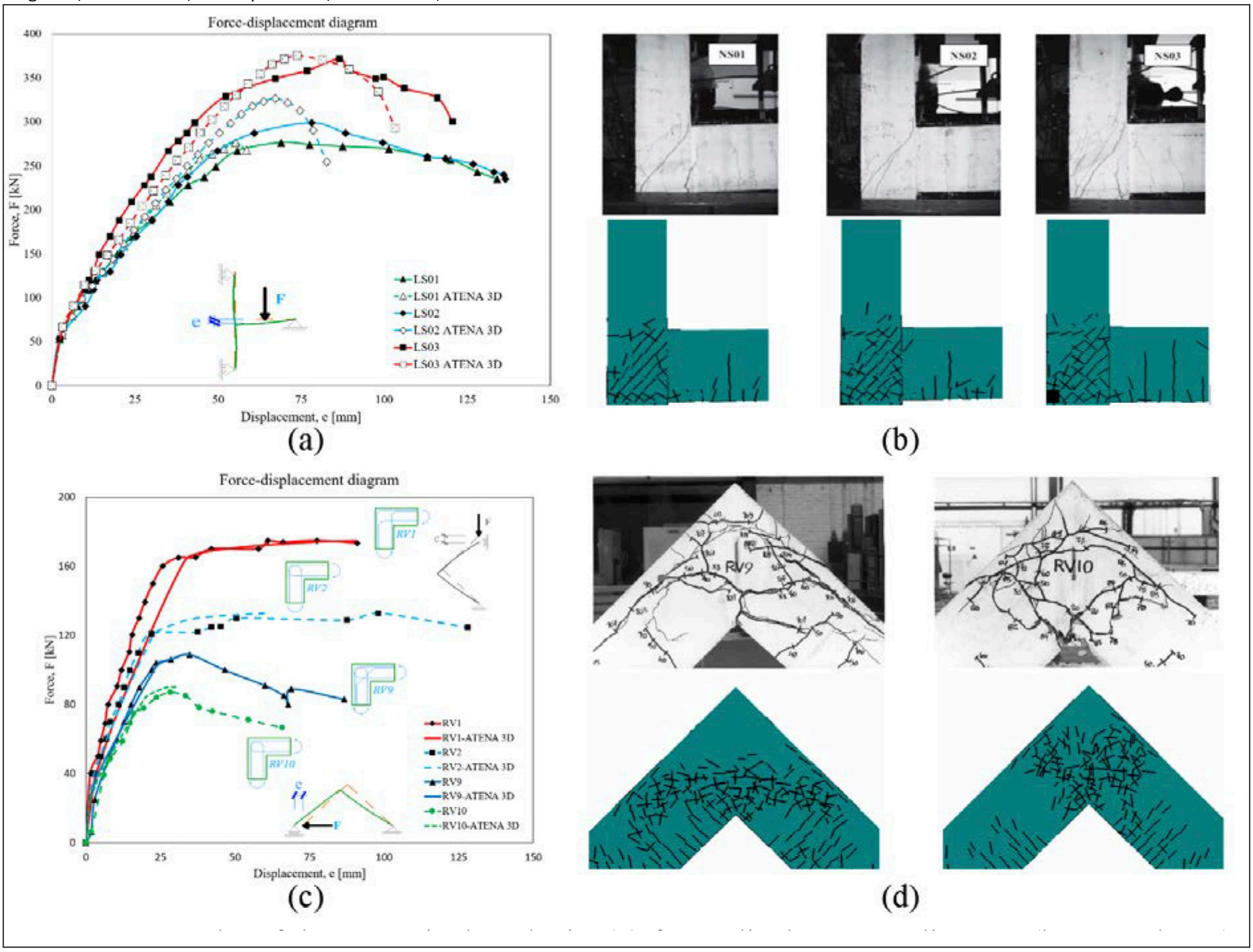
Fig. 3: Beam-column and frame corner connections: (a) ATENA 3D model (beam-column), (b) ATENA 3D model (frame corner), (c) static structure (beam-column), static structure (frame corner)

is possible to analyze the complex behaviour of monolithic reinforced concrete frame connections formed with the same reinforcement ratio but with different rebar placing under one-way monotonically increasing quasi-static loading instead of a very expensive series of laboratory experiments *(Figure 4(c))*.

With our improved modeling method, the real behaviour of cast-in-situ reinforced concrete beam-column connections (within a defined displacement limit) under horizontal cyclically varying directional loads *(Figure 5(a))* is extremely well-approximated by a finite element calculation within the given test range. During the individual finite element calculations, under horizontal quasi-static loads, we applied horizontal cyclically varying force loads, with which we were able to study the complex behaviour of the connections of the investigated specimens with sufficient accuracy. The connections made with the different placing patterns of reinforcement and stirrups can be modeled *(Figure 5(b), (c))*, using the modeling technique we have defined, by a nonlinear, three-dimensional finite element program within the given deformation range with sufficient accuracy to describe the behaviour (within 5-10%). To model the cyclically changing horizontal load, we compared the numerical models *(Figure 6)* produced with the improved version of the previously defined modeling technique, also with laboratory experiments found in the international literature (Masi, Santeriero, Nigro 2013). With the modeling technique developed, it is also possible to study the behavior of new, but even of existing cast-in-situ reinforced concrete structural joints against seismic, cyclic horizontal loads up to the deformation limits set in domestic and international standards (Roszevák, Haris, 2019).

The modeling method developed is also suitable for the analysis of point-supported flat slabs for vertical and horizontal loads. Using the verified numerical model, we showed in a geometric arrangement identical to the laboratory experiments that a linear computational framework model,

Fig. 4: Results of the numerical analysis: (a) force-displacement diagram (beam-column), (b) crack patterns (beam-column), (c) force-displacement diagram (frame corner), crack patterns (frame corner)



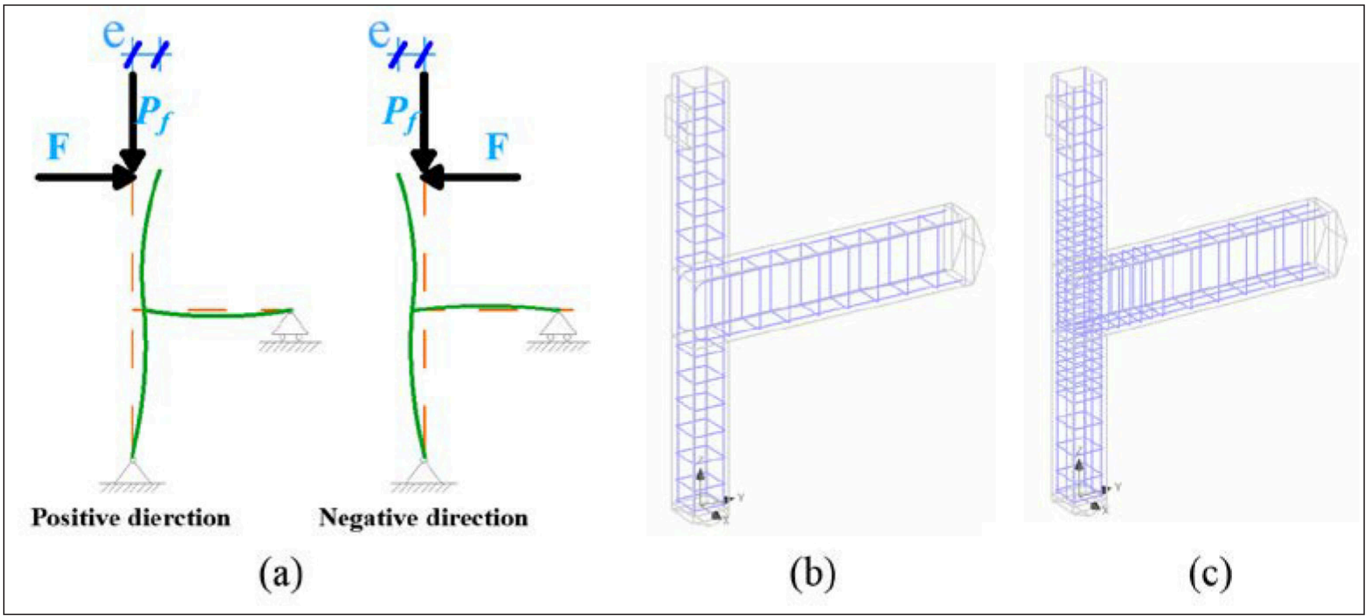
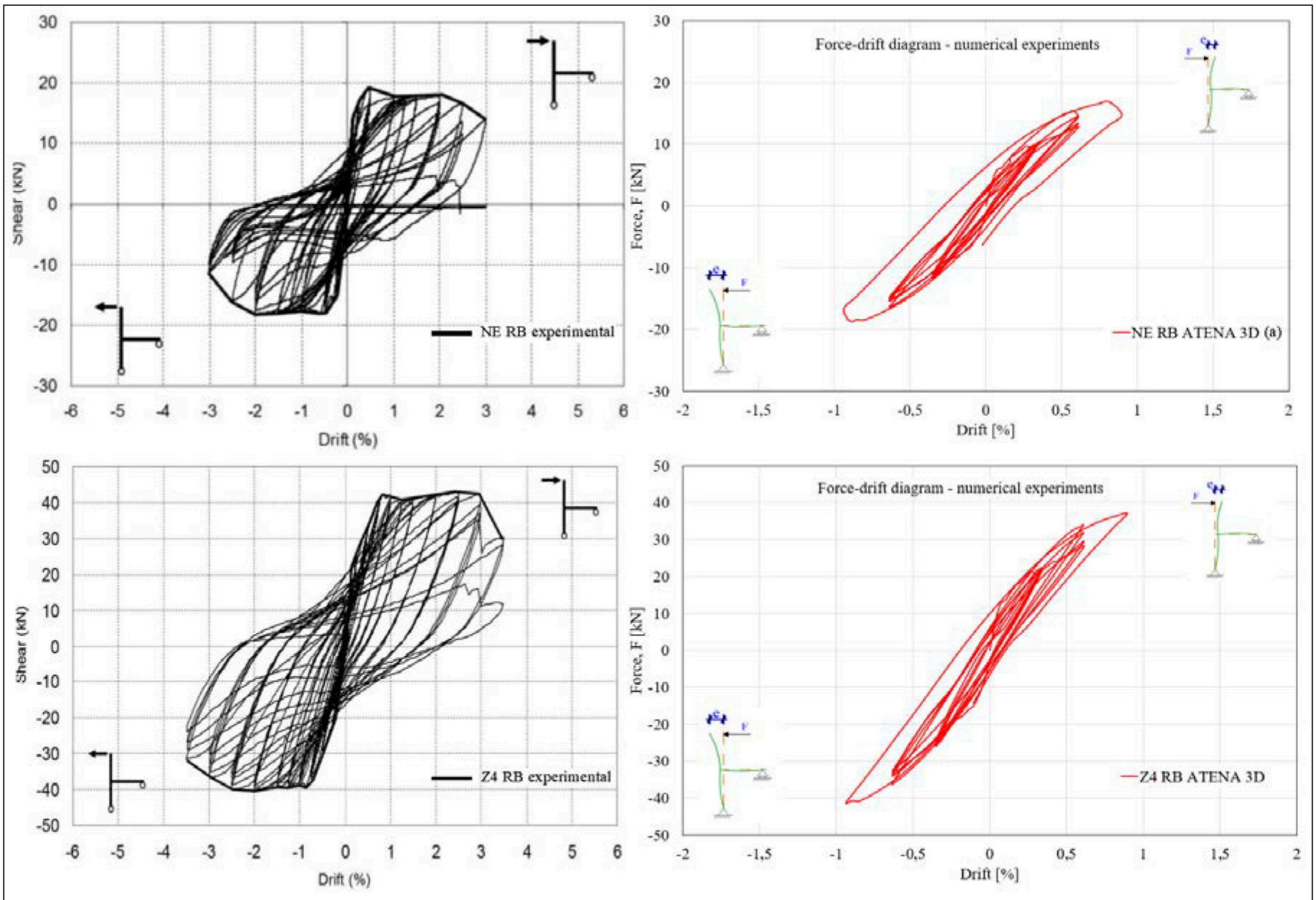


Fig. 5: *Beam-column connections: (a) static structure and loading, (b) ATENA 3D model (NE FB), (c) ATENA 3D model (Z4 RB)*

approximating the results of nonlinear virtual experiments describing the behavior of column-supported flat slabs, can be generated using an equivalent beam width method. We have shown that the modeling method is suitable for a more accurate description of real structural behavioural stages with significant plastic deformations. By combining and geometrically extending the nonlinear numerical results and the much simpler but easier-to-use linearly flexible computational model, we have shown that a function of one or two variables suitable for recording the replacement plate width can be produced *(Figure 7.)*. It can specify the value of replacement reduction factors in proportion to the thickness of the slab, the cross-sectional size of the column, raster distribution, and the desired force-displacement (Roszevák, Bodó, Haris, 2019).

Using the results and experiences so far, we have also started to conduct research in a new direction. We examined the behaviour of connections (beam-column and column-cup-foundation) in a simple prefabricated reinforced concrete frame structure and the modeling capabilities of each connection (Roszevák, Haris, 2021). Basically, we made separate joint models of the prefabricated frame; however, using the results of the joint models, we also created a complex frame model *(Figure 8)*. The results obtained using

Fig. 6: *Comparison of numerical and experimental results*



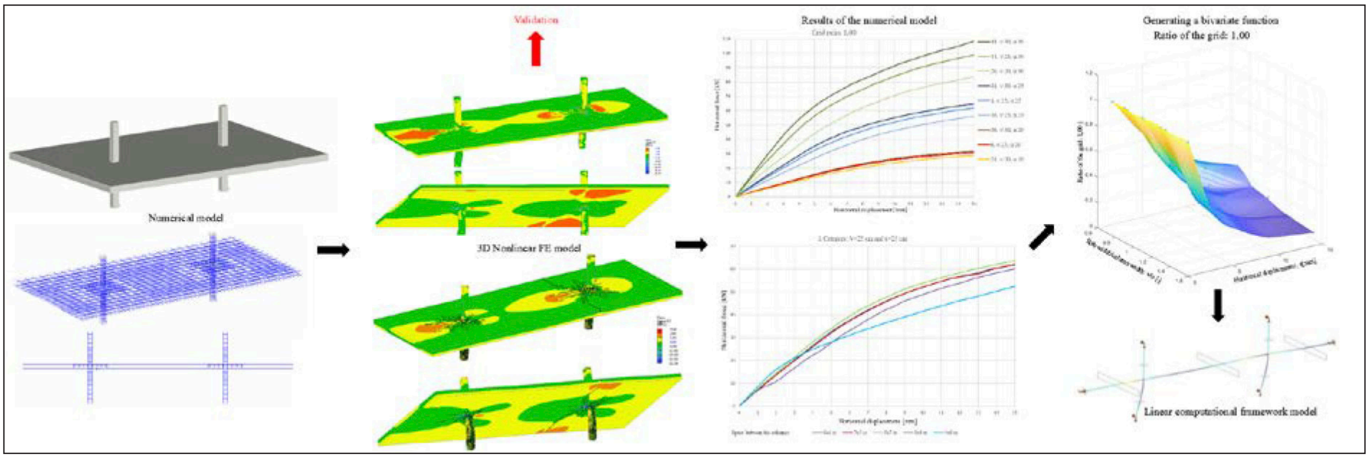


Fig. 7: Flowchart of the equivalent replacement framework model

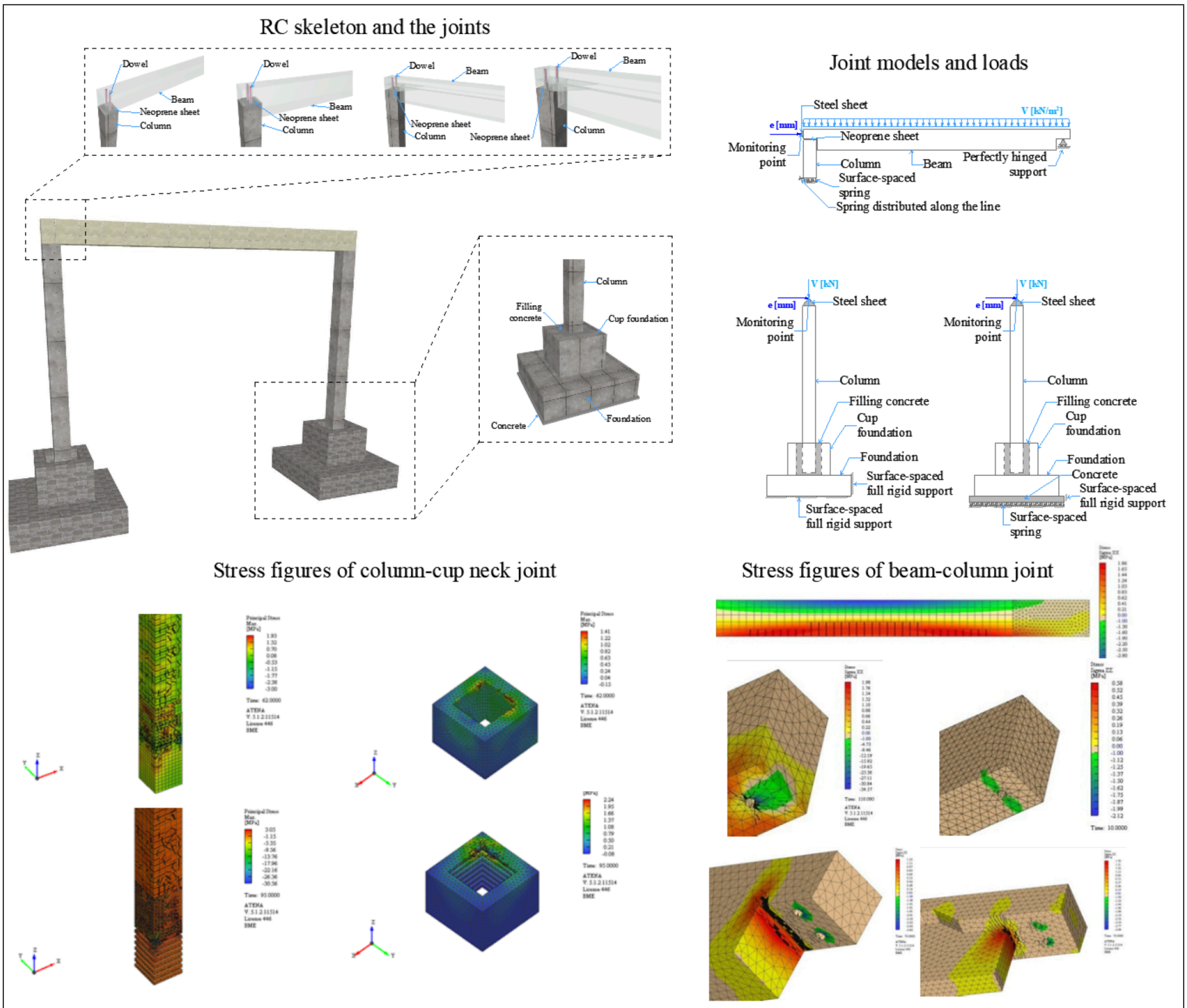


Fig. 8: Analysis of prefabricated RC skeleton

simple two-dimensional (linear and nonlinear) finite element models were compared with the results obtained using 3D nonlinear finite element joint models.

In the case of cup-foundation joints, we investigated the effect of the ribbed design of the lower part of the column, the possibility of modeling the shrinkage of the filling concrete between the cup neck and the column and we also started to investigate the possibilities of supporting the cast-in-situ reinforced concrete foundation. In the case of column-beam joints, we investigated the effect of the diameter and the number of rebar dowels on the behaviour of the joint. We also analyzed the effect of neoprene plate dimensions and the modeling possibilities of the filling mortar around the dowel and of the types of the beam's cross-section. Finally, we examined the effect of each joint design on the behavior of the global framework.

We also performed the tests of cast-in-situ reinforced concrete (stiffening) wall and slab connections (Roszevák, Haris, 2017) with unidirectional monotonically increasing quasi-static *(Figure 9)* and cyclically varying loads using the modeling procedure defined in our previously verified numerical models. Based on our results, it can be stated

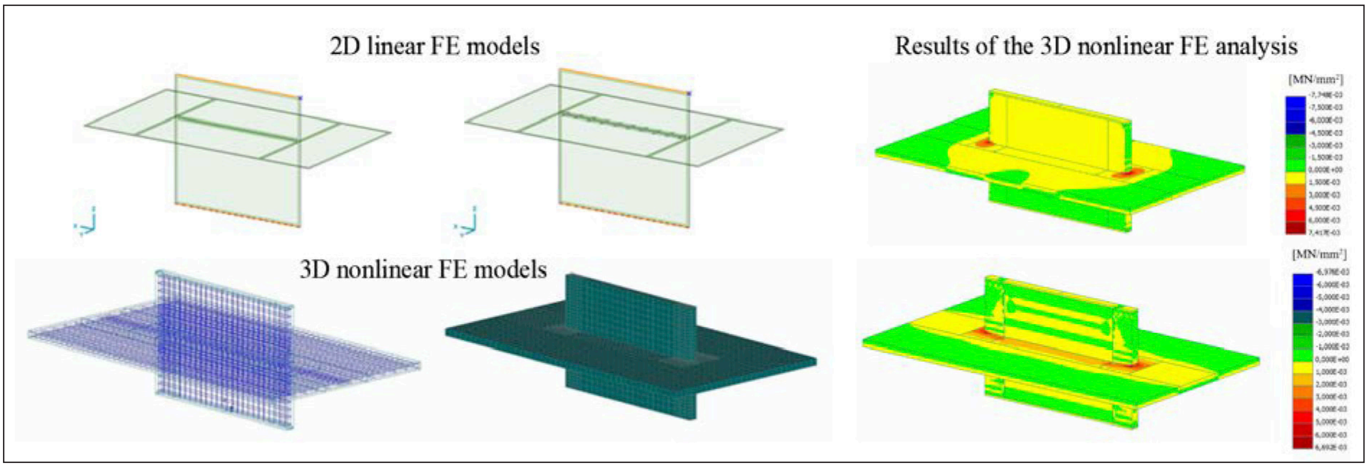


Fig. 9: Numerical models for wall-slab connections (quasi-static vertical loading)

that instead of the numerically infinitely large support at the bottom and top of the wall, spring support is more suitable for the study than in the case of the models made for cyclically changing direction load and unidirectional monotonically increasing load. By reducing spring support in proportion to stiffness, the finite element calculation does not result in a numerical error as in the case of "infinitely large" support. The reinforcing bars are spliced in the design of our test connections: side-by-side reinforcing bars must be placed in the cross-section of the joint at least at the same axial distance as a quarter of the diameter of the bars, so that the finite element calculation does not yet result in an error.

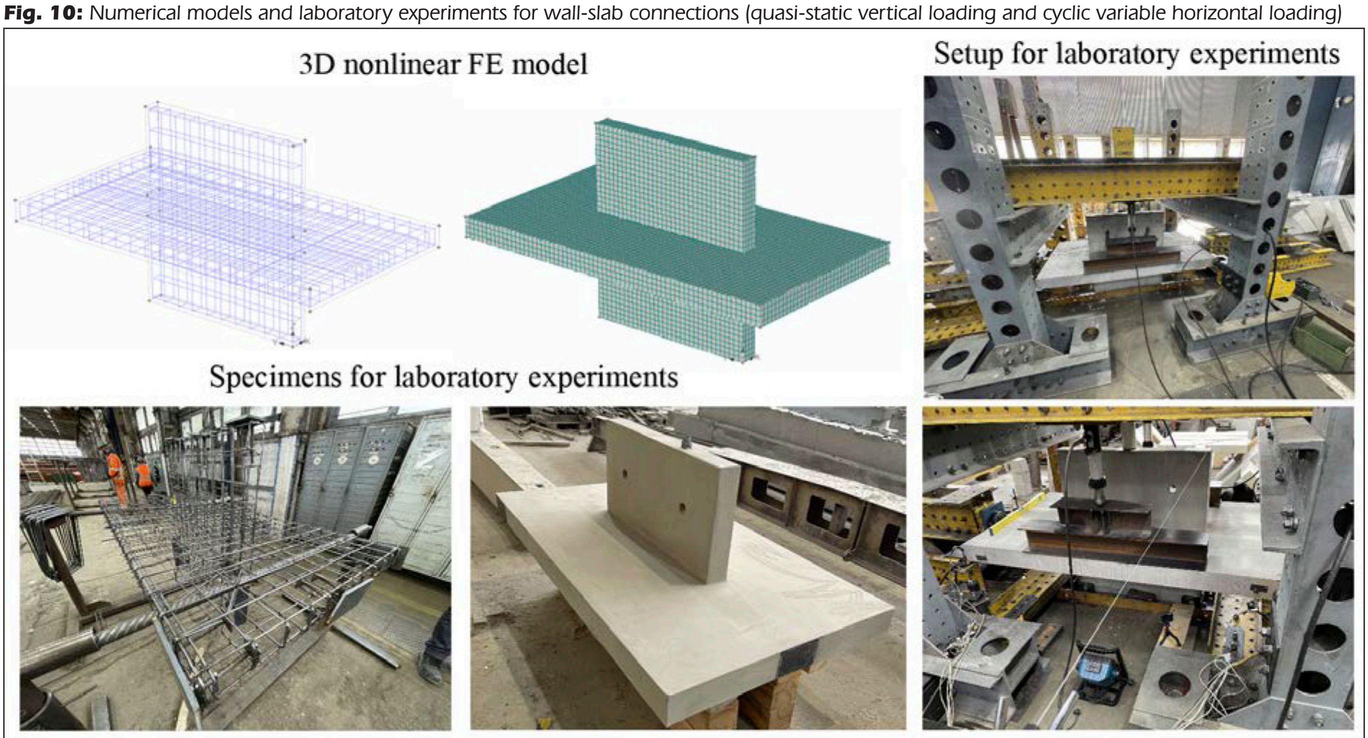
Recently and nowadays, cast-in-situ reinforced concrete stiffening walls are always tested under laboratory conditions on simplified experimental elements loaded in plane with specifically horizontal loads, without the associated structures. In the case of horizontal effects of cyclically varying direction and magnitude, descriptions of structural behavior should come to the fore even more in order to get a detailed understanding of the stiffness conditions of the cast-in-situ reinforced concrete wall-slab connection. Our goal is to investigate a unique element of a general torsional stiffening system, to accurately describe the structural behavior of a wall-slab connection both by numerical modeling and by the targeted laboratory testing of structural connections.

A series of 16 test specimens were designed to examine the structural elements *(Figure 10)*. The aim of the laboratory experiments is to study the actual design of the wall-slab connections and the effect of different modes of reinforcement placing on the joints and their effect on load-bearing capacity, stiffness, crack pattern and deformations. According to the results it is possible to verify high complexity and sophisticated three-dimensional nonlinear finite element models. Another goal is to describe the stiffness of the stiffening walls and the relationship between the stiffening walls and the slabs more accurately and efficiently, to supplement and/or clarify the designing formulas that can be used in everyday engineering practice, and to formulate structural design guidelines and recommendations.

4. CONCLUSIONS

In the field of cast-in-situ reinforced concrete structures, we performed several numerical studies, which were created with the modeling procedure we developed. In many cases, the performed numerical analyses were compared with the mostly international laboratory experiments found in

Fig. 10: Numerical models and laboratory experiments for wall-slab connections (quasi-static vertical loading and cyclic variable horizontal loading)



the literature. In our quasi-static studies, the results of the numerical models (cracking force, force of failure, peak force, displacement due to failure) showed only a difference of 5-10%. We also compared the crack patterns, which also showed a good agreement. Using the results and experiences obtained during our quasi-static studies, we also performed cyclic analyses, for which we also obtained very similar results (maximum difference: 10 %) within a certain rotation limit compared to the laboratory experiments. The results obtained during the cyclic studies can be extended to the case of larger deformations, which can be done by supplementing a modeling procedure. Based on the experience gained in the field of modeling of cast-in-situ reinforced concrete structures, we also extended the modeling procedure to the examination of prefabricated structural elements. Based on the study, it can be concluded that the joints and global behaviour of a simple prefabricated reinforced skeleton can be investigated with the modeling procedure developed and further developed by us. In any case, we need to compare the results with the results obtained in laboratory experiments to make sure that the modeling procedure is appropriate.

5. FURTHER RESEARCH OPPORTUNITIES

The results obtained and the modeling methods developed have laid the foundation for many studies by the research group we lead. Additional research areas as well as studies of structural designs have become available. Further developing the technique developed for the examination of basically cast-in-situ reinforced concrete structures, we are currently conducting research on prefabricated reinforced concrete structural elements and their connection design. The normal reinforced elements were started to be examined in respect of the foundation (column-cup neck) and column-beam relationship of a simple precast reinforced concrete skeleton. The modeling procedure available is elevated to a more advanced level by examining the prestressed structural elements of the prefabricated reinforced concrete and their connection design. Current research is underway on prefabricated prestressed reinforced concrete beams and prefabricated prestressed hollow core slabs. It should also be noted that the modeling procedure developed is also used in the numerical analysis of masonry structural element(s).

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