Virtual Lab for Fibre Reinforced Concrete Design by Simulation Prototyping

FibreLAB

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D4.2 Software for FRC Design and Assessment

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http://www.fibrelab.eu

Executive summary:

This is the FibreLAB project document. This document is being continuously updated during the project. The current version extends the previous report, which describes the software prototype for FRC design and assessment. This work is part of workpackage W4. In this work package methods and software tools will be developed to facilitate the actual design or assessment of fiber reinforced concrete structures or products. This involves the automatic generation of the necessary numerical model for the various design checks, their automatic execution, evaluation of the outcome of the performed checks and if necessary design adjustments if the required performance based criteria are not satisfied.

The project will develop a software tool to support the design of advanced structures or products from fiber reinforced concrete (FRC) using simulation prototyping. The software will support engineers during the design process, which will be based on the simulation of the structural performance during the foreseen design scenarios for the individual design limit states: serviceability and ultimate limit states as well as the new design states such as: robustness, durability and service life verification.

The software will be developed based on the existing product ATENA developed and distributed by CER. The project will develop a separate module of this system specifically targeted for fibre reinforced concrete industry.

This product can be used separately or together with the existing ATENA software. The product shall also support parametric modelling and embedded scripting language to enable the fast development of even more specialized design tools for the development and design of specific construction products for pre-cast industry or other mass production.

Revision history:

date	author	status	changes
09.11.2018	J. Červenka	1.0	draft
18.1.2019	J. Červenka	2.0	First complete version
20.1.2019	P. K. Juhasz	3.0	Addition of Debrecen stadium example

Table of contents:

1. General

In this work package methods and software tools have been developed to facilitate the actual design or assessment of fiber reinforced concrete structures or products. This report summarizes the latest state of development. This work is divided into the following tasks:

Task 4.1: SLS & ULS FRC Design & Assessment

This task will work on the automatic development of the numerical models based on the parametric geometric models developed in WP2. The developed models, loading schemes and solution techniques will be used for checking service limit state (SLS) and ultimate limit states (ULS) for fiber reinforced concrete structures and/or products. The design and assessment process will be based on nonlinear simulation and the global safety format. The safety formats for the SLS and ULS check will be based on existing standards proposed in the national codes if available. If such safety formats are not available the international fib model code 2010 formats will be used. The initial project development will concentrate mainly on Eurocode support, but future extension to other national standards should be possible.

Task 4.2: Fatigue FRC Design & Assessment

Fatigue design is a special case of ULS design. It will be treated however by a separate task, since the development of special material model will be necessary. This model development will be based on existing model in ATENA developed in previous research projects for normal concrete, but research and development is necessary for the model extension to fiber reinforced concrete.

Task 4.3: Fire FRC Design & Assessment

Fire design can be also considered to be a special case of ULS design. ATENA software includes special model for the analysis of concrete-like materials subjected to very high temperatures such as for instance fire. This model has been developed during previous European project UPTUN, and has been successfully used for reinforced concrete. The model can be adopted for fiber reinforced concrete. More research is however necessary since the existing laws and formulas for nonlinear thermal analysis and for thermal dependency of mechanical properties should be further developed and validated for fiber reinforced concrete material.

Task 4.4: Service Life Design & Assessment

ATENA supports simulation of material long term degradation due to carbonation, chloride ingress and the resulting corrosion process. This analytical module has been developed in a previous research project CERHYD funded by the Czech Ministry of Industry and Commerce. The simulation techniques and numerical models are available now, but research and development is necessary for their proper introduction into the design process. Service life limit states are relatively new topics in the construction industry, and there now standards yet available. This presents a huge opportunity for the consortium since members of the team participate in the European as well as international committees working on the new standards in this area. In the future strong demand can be expected for software tools based on service life design.

2. Global Structural Assessment Approaches

Since the design codes for FRC structures are generally not available, computer simulation based on nonlinear finite element analysis has a big potential in investigation and design of these structures. This chapter is focused on assessment of these structures by safety formats published in the new *fib* Model Code 2010 [1] where rational safety assessment approach is presented, which reflects new developments in safety formats based on probabilistic methods. By these approaches, numerical results can be introduced into a suitable engineering safety concept. This document supported the results of authors' research project presented in [2] where comparison of global safety determined by several methods was presented. The investigation described in [2] included typical ordinary reinforced concrete structures with bending, shear-bending or compression failure modes and confirmed that simplified global safety formats can be used for design and structural verification. In this chapter, previous calculations for RC structures are extended by the study of safety formats of the two fibre reinforced concrete structural elements [3], such as tunnel lining precast segment.

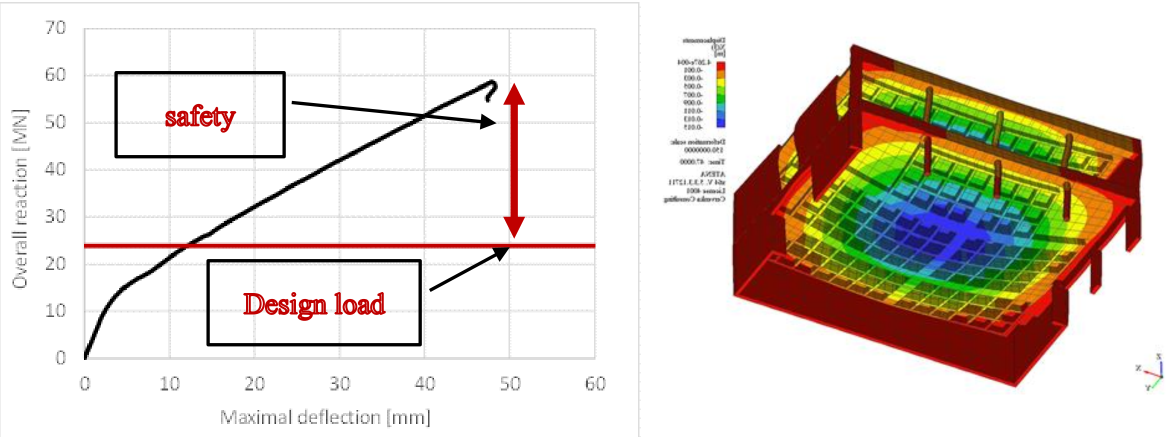


Figure 1: Global assessment approach

2.1 Assessment of Structural Safety and Reliability

Reliability and safety of reinforced concrete structures can be verified by several safety formats calculated by nonlinear analysis that are proposed in *fib* Model Code 2010:

- Full Probabilistic Analysis,
- ECOV Method – Estimate of Coefficient of Variation,
- Method based on EN 1992-2,
- Partial Safety Factors (PSF).

The same safety formats can be applied also for fibre reinforced concrete structures. Design combining numerical and experimental investigations together with safety formats is appropriate method how to obtain safe and reliable structure.

2.1.1 Full Probabilistic Analysis

The full probabilistic approach represents the most accurate method for the safety assessment of civil engineering structures. The accuracy of this approach is much higher if the nonlinear structural analysis is used as a limit state function. The numerical simulation resembles a real testing of structures by considering a representative group of samples, which can be statistically analyzed for the assessment of safety. This concept is supported by the new *fib* Model Code 2010 [1] where rational safety assessment approach is presented, which reflects new developments in safety formats based on probabilistic methods. In the Chapter 4 on *Principles of structural design* the probabilistic safety format is introduced as a general and rational basis of safety evaluation. In addition to the partial factor format (which remains as the main safety format for most practical cases) a global resistance format is recommended for nonlinear analysis.

In case of fibre concrete structures the design codes are generally not available or not sufficient. Therefore, the computer simulation based on advanced nonlinear finite element analysis has a big potential in design of these structures. The numerical results can be introduced into a suitable engineering safety concept, from which the fully probabilistic analysis is the ultimate tool for design and safety assessment. It is superior to simplified methods because it provides information on the variability of resistance. However, it is computationally demanding and requires good information about random properties of input variables. Therefore, it is applied in special cases, where consequences of failure substantiate the increased effort.

The probabilistic analysis is performed here using software SARA, which integrates ATENA [4] and FReET program tools. The variability of basic properties is described by distribution functions and its parameters (mean, standard deviation, etc.). Probabilistic analysis of the resistance is performed by numerical method such as Latin hypercube sampling (LHS) method. Resulting set of resistance values is approximated by a probability distribution function (PDF) of global resistance, and describes the random properties of the resistance. Finally, for a required reliability index β, or failure probability P_f, a value of the design resistance R_d shall be calculated.

Probabilistic analysis is an efficient tool for safety assessment of civil engineering structures, in particular of concrete or fibre concrete structures. In the probabilistic nonlinear approach the structural resistance R_d is calculated by means of the probabilistic nonlinear analysis. The classical statistical and reliability approach is to consider material parameters as random variables with prescribed distribution function. The stochastic response requires repeated analyses of the structure with these random input parameters, which reflects randomness and uncertainties in the input values (see e.g. [5]). In this approach, the resistance function $r(r)$ is represented by nonlinear structural analysis and loading function $s(s)$ is represented by action model. Safety can be evaluated by the reliability index β, or alternatively by failure probability P_f taking into account all uncertainties due to random variation of the input values – material properties, dimensions, loading, and other.

Probabilistic analysis based on the nonlinear numerical simulation includes following steps:

- *Numerical model based on the nonlinear finite element analysis.* This model describes the resistance function $r(r)$ and performs a deterministic analysis of resistance for given set of input variables.
- *Randomization of input variables* (material properties, dimensions, boundary conditions, etc.). This can also include some effects of actions, which are not in the action function $s(s)$ (for example pre-stressing, dead load etc.). Random properties are defined by random distribution type and its parameters (mean standard deviation, etc.). They describe the uncertainties due to statistical variation of resistance properties.

- *Probabilistic analysis of resistance and action.* This can be performed by stratified method of Monte Carlo-type of sampling, such as LHS sampling method. Results of this analysis provide random parameters of resistance and actions, such as mean, standard deviation, etc. and the type of distribution function for resistance.
- *Evaluation of safety* using reliability index β or failure probability P_f.
- Probabilistic analysis can be also used for *determination of design value of resistance function r(r)* expressed as R_d. Such analysis involves repeatedly the first three steps above, and R_d is determined for required reliability β or failure probability P_f.

In order to make the application of the probabilistic nonlinear analysis user-friendly, special software tool has been developed by the authors and their co-workers. The resulting software SARA (Structural Analysis and Reliability Assessment) integrates software tools ATENA and FReeT. It is equipped with a user-friendly shell called *SARA Studio ()*, which leads the user interactively through the modelling and randomization process of the solved problem as described above. All features (or just selected ones) of the involved programs including modelling of deterioration/degradation phenomena can be utilized also in the reliability analysis and performance-based assessment of concrete structures. For this purpose, the interconnectivity between ATENA Engineering as well as ATENA Science (i.e. ATENA input file), with the probabilistic modules was achieved. The program control and data exchange is organized by an efficient and user friendly shell interface (Figure 3).

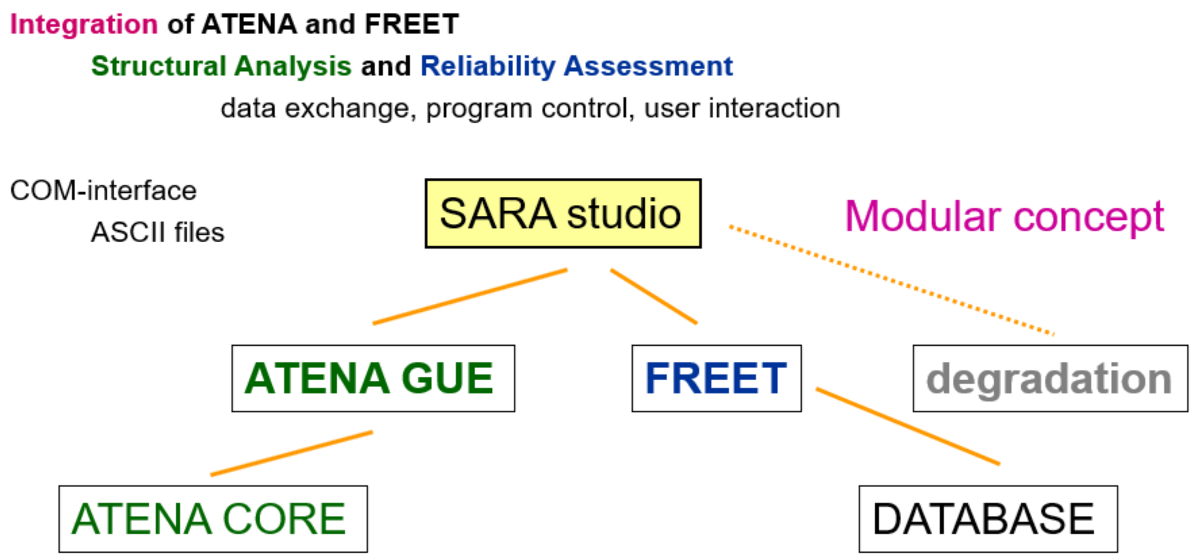


Figure 2: Integration of ATENA and FREET in SARA Studio

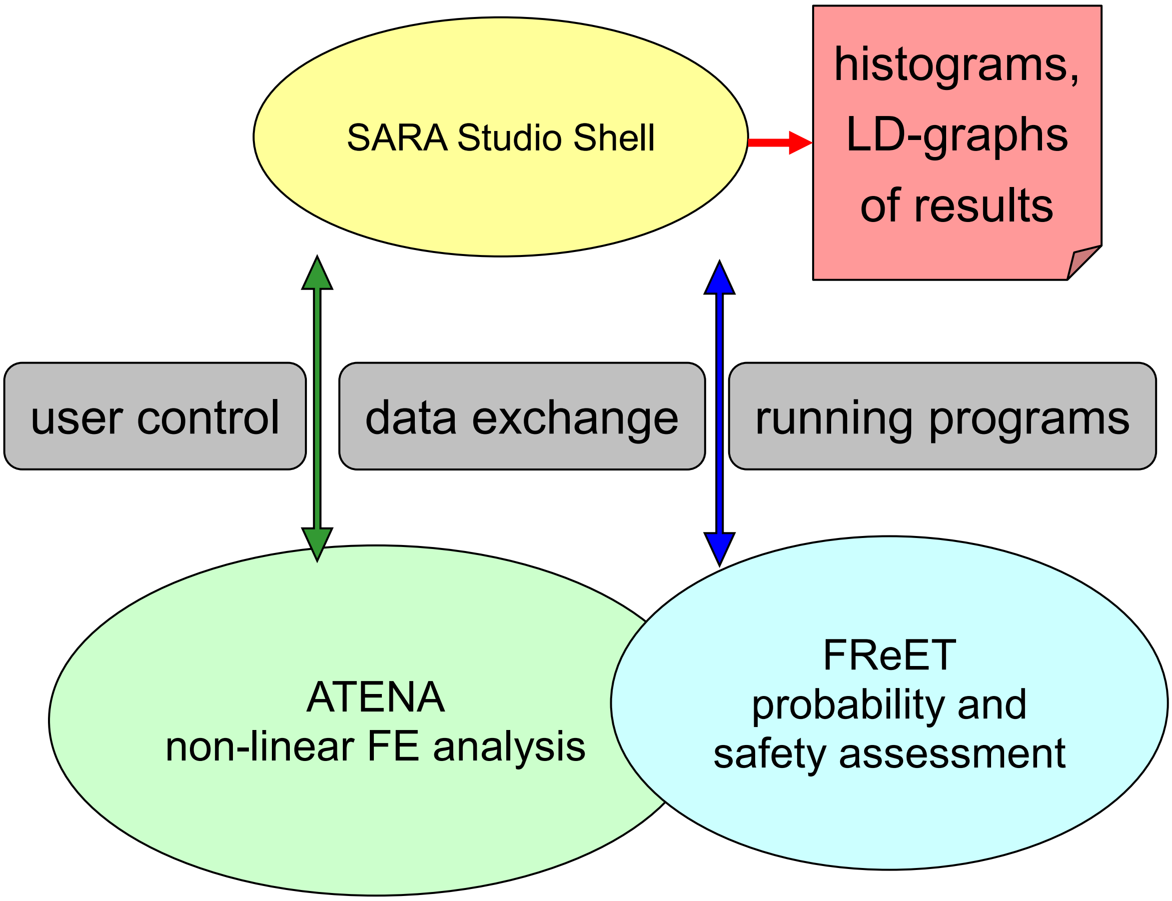


Figure 3: Structure and data flow in the SARA system

2.1.1.1 Stochastic analysis

The stochastic analysis is based on repeated analysis of the prepared model with randomly generated properties. Since each of these samples represent a demanding nonlinear finite element analysis, the number of samples should be kept on moderate level. In the same time the applied methodology should be sufficiently accurate and representative.

The probabilistic software FReET [6] has been developed for stochastic and probabilistic analysis of computationally intensive problems such as nonlinear finite analysis. Stratified simulation technique LHS is used to keep the number of required simulations at an acceptable level. This technique can be used for both random variables and random fields levels. Statistical correlation is imposed by the stochastic optimization technique called simulated annealing. Sensitivity analysis of the input parameters to resulting values is based on nonparametric rank-order correlation coefficients. Procedure can be briefly outlined:

- random input parameters are generated according to their PDF using LHS sampling
- samples are reordered by the Simulated Annealing approach in order to match the required correlation matrix as closely as possible
- generated realizations of random parameters are used as inputs for the analyzed function (computational model)
- solution is performed many times and the results (structural response) are saved

- simulation process the resulting set of structural responses is statistically evaluated

Main results from the stochastic analysis are:

- estimates of the mean value
- variance
- coefficient of skewness and kurtosis
- empirical cumulative probability density function estimated by an empirical histogram of structural response

This basic statistical assessment is visualized through histograms. This is followed by reliability analysis based on several approximation techniques:

- estimate of reliability by the Cornell safety index β
- curve fitting approach applied to the computed empirical histogram of response variables
- estimate of probability of failure based on the ratio of failed trials to the total number of simulations

State-of-the-art probabilistic algorithms are implemented to compute the probabilistic response and reliability. The main features of the FReET software are:

(a) stochastic model (inputs)
- direct connectivity to the nonlinear analysis input data
- friendly Graphical User Environment (GUE)
- 30 probability distribution functions (PDF), mostly 2-parametric, some 3-parametric, two 4-parametric (Beta PDF and normal PDF with Weibullian left tail)
- unified description of random variables optionally by statistical moments or parameters or a combination of moments and parameters
- PDF calculator
- statistical correlation (also weighting option)
- categories and comparative values for PDFs
- basic random variables visualization, including statistical correlation in both Cartesian and parallel coordinates

(b) probabilistic techniques
- Crude Monte Carlo simulation
- Latin Hypercube Sampling (3 alternatives)
- First Order Reliability Method (FORM)
- Curve fitting
- Simulated Annealing
- Bayesian updating

(c) response/limit state function
- numerical form directly connected to the results of nonlinear FE analysis
- multiple response functions assessed in same simulation run

2.1.2 ECOV Method – Estimate of Coefficient of Variation

ECOV method proposed by Cervenka in [7] is based on the idea, that the random distribution of resistance due to material, which is described by the coefficient of variation V_m, can be estimated from mean R_m and characteristic values R_k of resistance. The underlying assumption is that random distribution of resistance is according to the lognormal distribution, which is however typical for the structural resistance. Considering these assumptions the coefficient of variation V_m can be expressed as:

$$V_m = \frac{1}{1.65} \ln\left(\frac{R_m}{R_k}\right) \tag{1}$$

Then the global safety factor γ_R of resistance can be calculated as:

$$\gamma_R = \exp(\alpha_R \beta V_R), \quad V_R = \sqrt{V_m^2 + V_{Rd}^2} \tag{2}$$

where α_R is the sensitivity factor for resistance (as defined by FORM) and β is the reliability index. V_{Rd} is the model uncertainty. The above procedure enables to estimate the safety of resistance in a rational way, based on the principles of reliability accepted by the codes. Appropriate code provisions can be used to identify these parameters. For instance in the case of Eurocode EN 1990, typical values are $\beta = 3.8$ (50 years) and $\alpha_R = 0.8$, which corresponds to the failure probability P_f=0.001. The global resistance factor is then:

$$\gamma_R \cong \exp(3.04\, V_R) \tag{3}$$

and the design resistance is calculated as:

$$R_d = R_m / \gamma_R . \tag{4}$$

The main task in this method is the determination of the mean and characteristic values of resistance R_m, R_k. They can be calculated by two separate nonlinear analyses using mean and characteristic values of the input material parameters, respectively. The method is very general and reliability level β and distribution type can be changed if required. It can capture different types of failure and the sensitivity to a random variation of the material parameters is automatically included. The slight disadvantage of this method is the need for two separate non-linear analyses.

2.1.3 Method based on EN 1992-2

Eurocode for bridges introduced a concept for global safety verification based on nonlinear analysis. In this approach, the design resistance is calculated from

$$R_d = R(f_{ym}, \tilde{f}_{cm} ...) / \gamma_R \tag{5}$$

where $f_{ym}, \tilde{f}_{cm}$ are mean values of material parameters of steel reinforcement and concrete, $f_{ym} = 1.1\, f_{yk}$ and $\tilde{f}_{cm} = 0.843\, f_{ck}$. The concrete mean value is reduced to account for the higher variability of concrete property. This method is described in more detail in [8]. The global factor of resistance is then $\gamma_R = 1,27$. The evaluation of the resistance function is done by a single nonlinear analysis assuming the material parameters according to the above rules.

2.1.4 Partial Safety Factors

This approach is the natural extension of the standard partial safety factor method, which is used in the most design codes. The design condition is formulated as

$$E_d < R_d \tag{6}$$

The design action $E_d = E(F, \gamma_G, \gamma_Q, \gamma_P, ..)$ is a function of the representative load F, which is multiplied by the partial safety factors $\gamma_G, \gamma_Q, \gamma_P, ..$ for permanent loads, live loads, pre-stressing, etc. The resistance $R_d = R(f_d)$ is calculated by a nonlinear analysis using design values of the material parameters $f_d = f_k / \gamma_M$, where f_k are characteristic values and γ_M partial safety factors of materials. The verification of safety by the condition (6) in the standard design practice is applied to cross sections and actions that are obtained by a linear analysis. It is well known that this concept is not consistent, since different methods are used for the calculation of actions (linear analysis) on one side, and for the resistance of cross sections (nonlinear) on the other. Furthermore, only local safety check is exercised and a global safety assessment is not performed, and is unknown. The action E_d in condition (6) is considered on the global level (for example live load intensity) and the resistance R_d is an ultimate load intensity obtained by a nonlinear analysis, in which design values of material parameters f_d are used.

2.2 Validation of Safety Formats for Ordinary Reinforced Concrete Structures

Validation of the safety formats described in the previous chapter can be found in the studies [2] and [7], where the calculated examples are described in more detail. The summary of results is shown in Table 1. This table shows the resistance for the four presented methods and 7 examples are listed and compared. To enable the comparison the results are normalized with respect to the resistance obtained by the PSF method. It should be noted that the study does not reflect the model uncertainty in a consistent way. The methods PSF and EN1992-2 include a model uncertainty, while in the ECOV and full probabilistic analysis the model uncertainty was considered, i.e. $V_{Rd} = 0$ which will enable an evaluation of the model uncertainty. This can explain the average results of ECOV method being slightly higher than the other two methods.

Table 1: Case study of safety formats for RC structures (R_d is normalized with respect to PSF)

	R_d/R_d^{PSF}			
	PSF	Probabilistic	ECOV	EN 1992-2
Example 1 - bending	1	0.96	1	0.95
Example 2 - deep shear beam	1	0.98	1.02	0.98
Example 3 - bridge pier, geom. nonlinear	1	1.02	1.06	0.98
Example 4 - bridge frame	1	1.01	0.97	0.93
Example 5 - shear beam w/o ties	1	0.97	0.95	0.99

Example 6 - shear beam w. ties	1	1.23	1.28	1.01
Example 7 - long-span girder	1	1.19	1.13	1.04
Average	1	1.05	1.06	0.98

2.3 Performance of FRC Structures

Two examples presented in chapter 4 were used for validation of safety formats for the modelling of fibre reinforced concrete. Results in Table 2 indicate that the global safety formats for nonlinear analysis are applicable to fibre reinforced concrete as well as for ordinary reinforced concrete as presented in [2] and [7]. Similarly to the previously published results, there does not appear to be a significant difference between the design resistances calculated by the investigated methods. It is observed that the EN 1992-2 approach gives in most cases more conservative results than the other methods. On the contrary the probabilistic and ECOV approaches give mostly slightly higher resistance values. This can be however attributed to the fact that they do not include model uncertainties, which are partially included in the PSF and EN 1992-2 methods. Due to high variability of FRC material properties it can be recommended to utilize preferably the stochastic analysis based methods, i.e. full probabilistic analysis or ECOV method, where the actual material variability can be accounted for the evaluation of structural performance, safety and reliability under severe conditions.

Table 2: Safety format results for FRC structures (R_d is normalized with respect to PSF)

	R_d/R_d^{PSF}			
	PSF	Probabilistic	ECOV	EN 1992-2
FRC bending	1	1.16	1.23	0.97
FRC tubing	1	1.22	1.27	1.00
Average	1	1.19	1.25	0.99

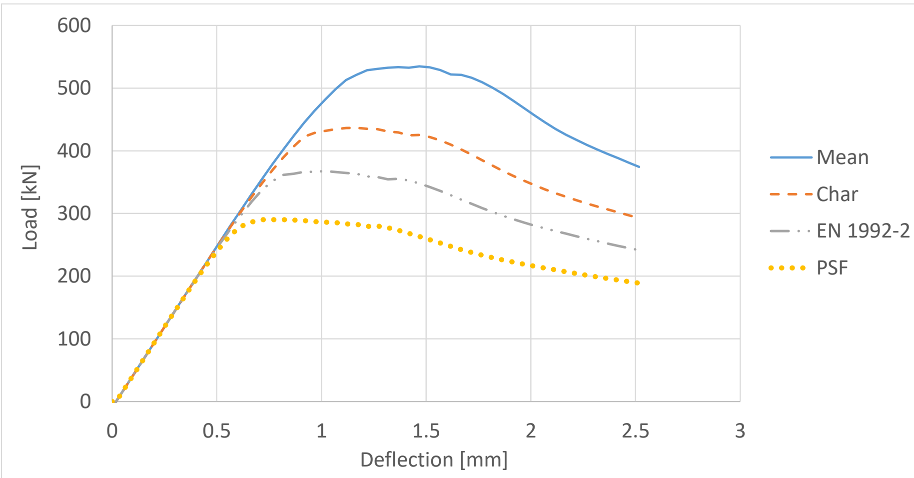


Figure 4: Calculated load-displacement curves for FRC tunnel tubbing example for various safety formats

3. ATENA Software Prototype version 6.0.0

ATENA software project prototype has been developed in the second year of the project in agreement with the original project proposal. The individual parts of the model are summarized in the various project reports: [14], [15] and also in the Section 2 of this report.

(1) Fast prototyping tool and pre-processor is described in the report [14]. This software is used for the parametric preparation of the numerical model as shown in Figure 5

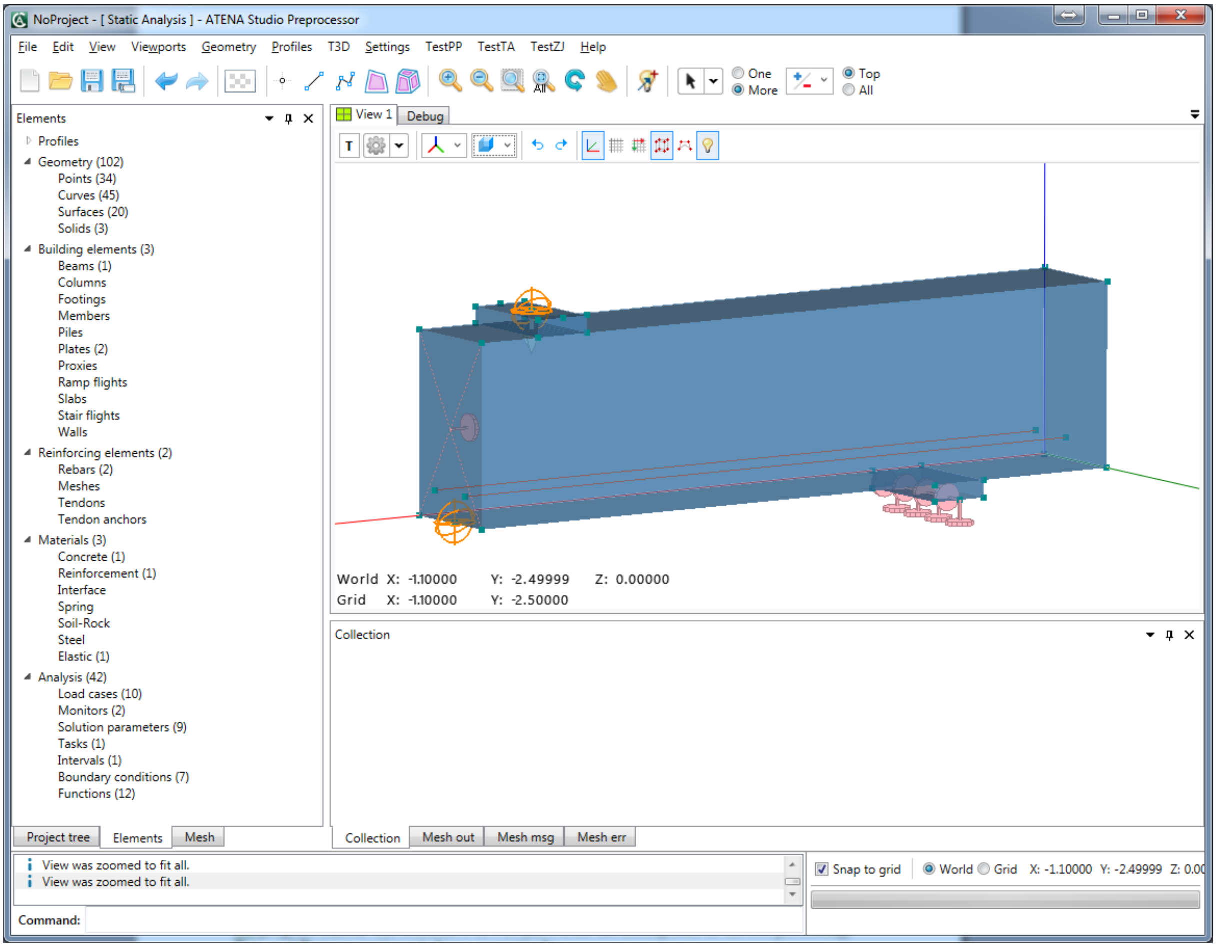


Figure 5: Main window of the prototyping and pre-processing tool

(2) Support for the building information model on the basis of IFC data format is also part of this pre-processing and prototyping tool as described in more detail in the report [14]

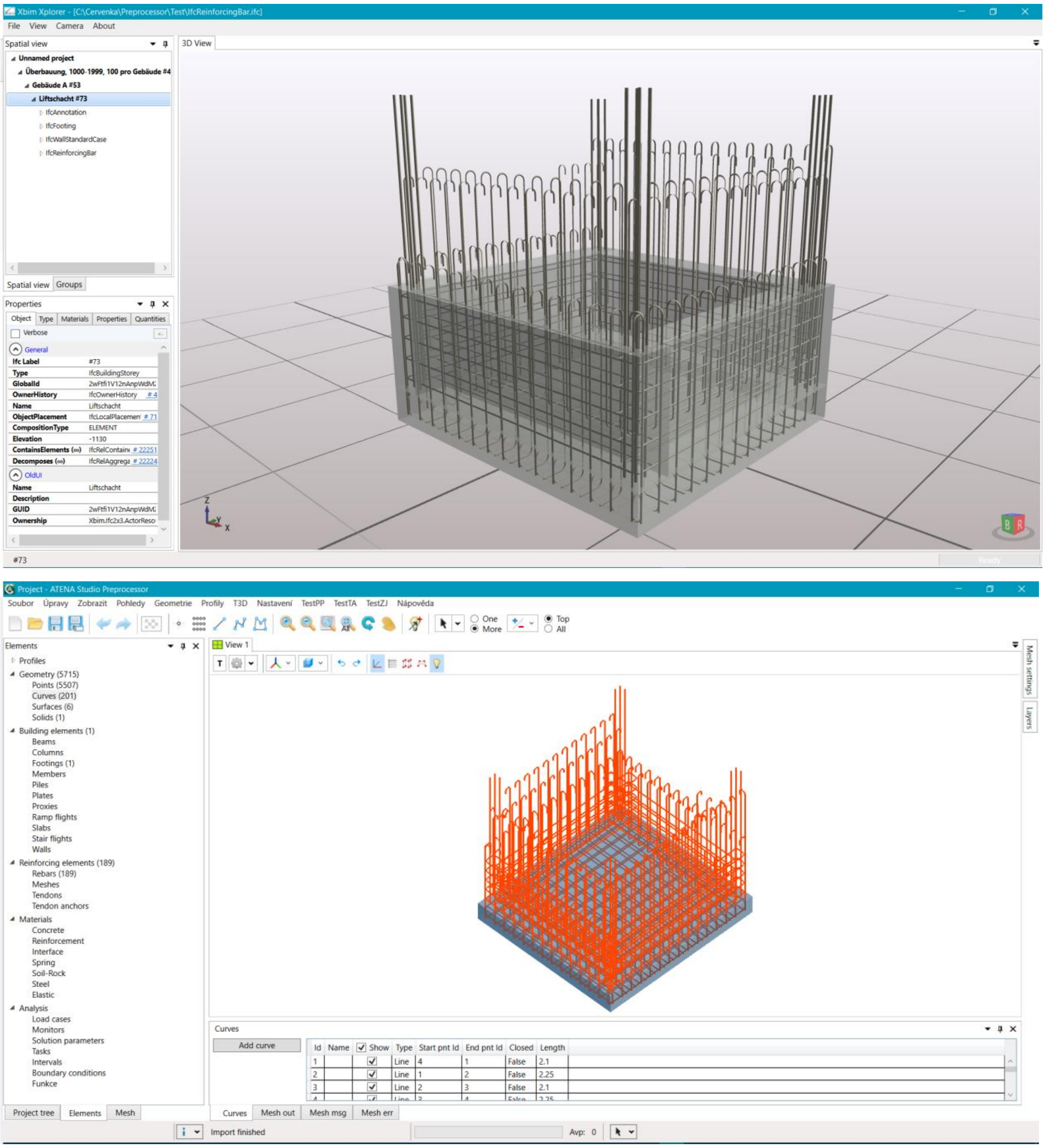


Figure 6: IFC test file previewed in the xBIM Xplorer before and after import to ATENA/Pre

(3) Advanced FRC material models and parameter identifications are described in more detail in the report [15]. Important tool in this taks is the software for parameter optimization and identification (see Figure 7).

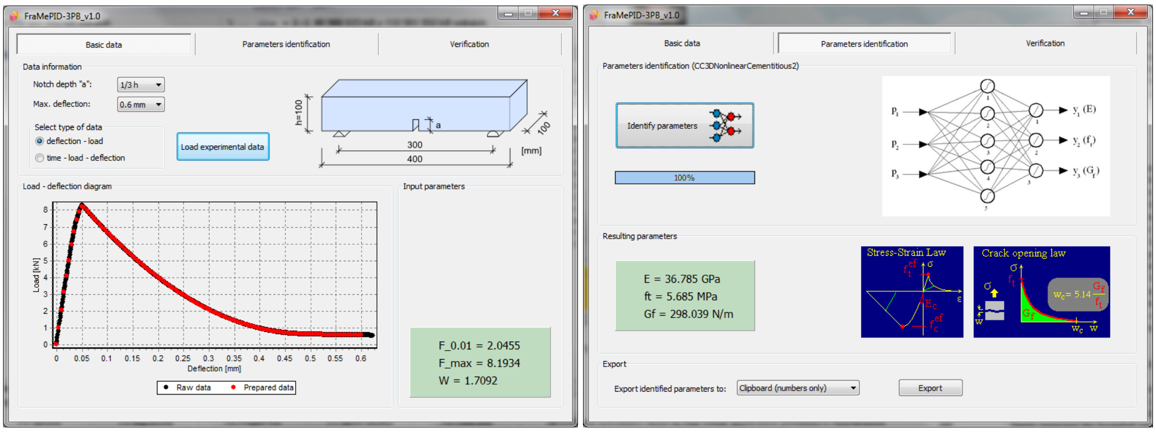


Figure 7: Optimization and identification prototype tool

(4) Advanced modelling approaches for fire or fatigue modelling are described in the theoretical manual [4].

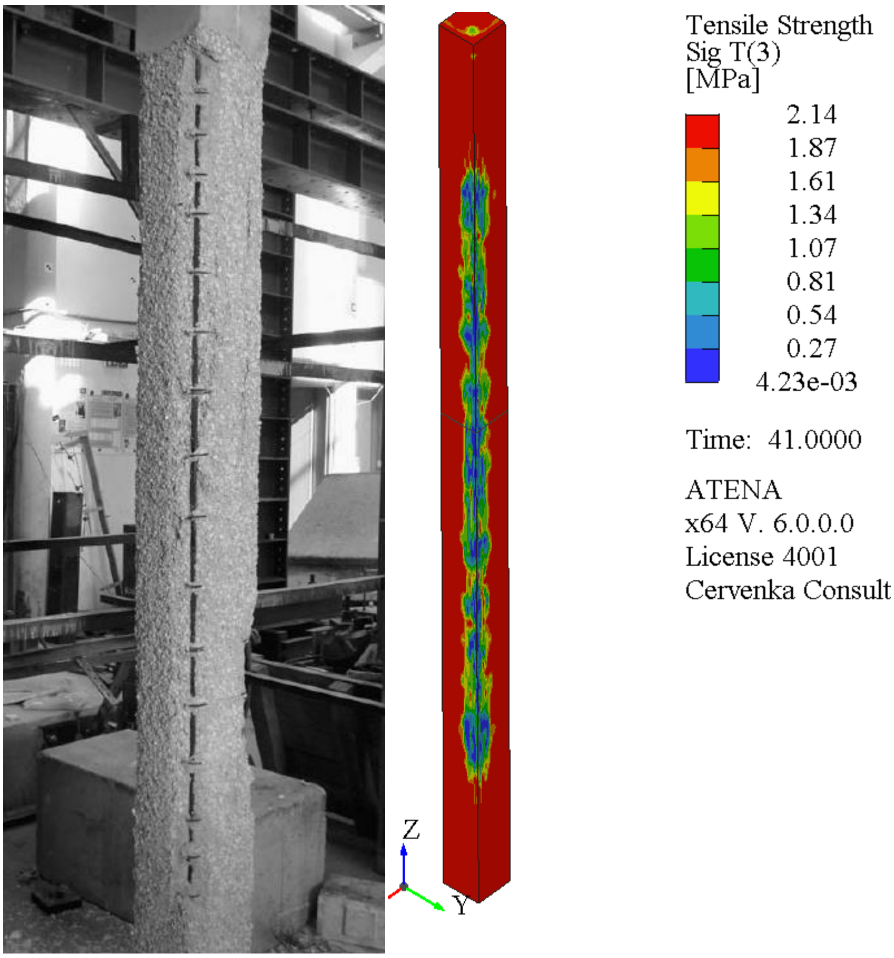
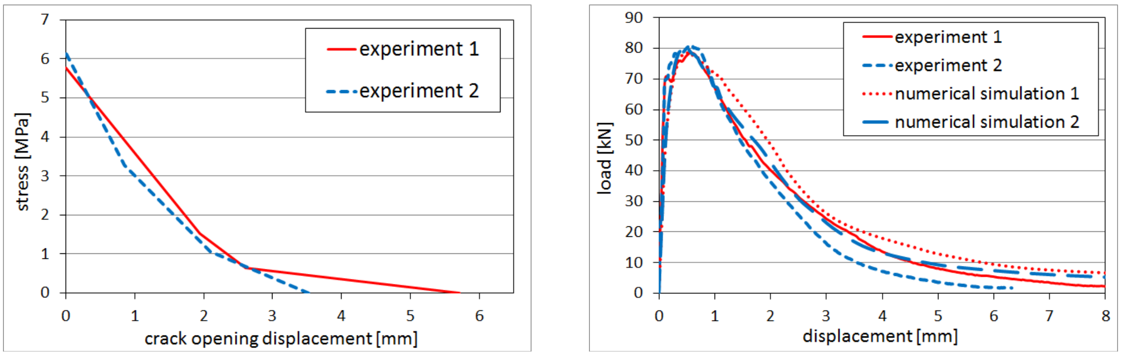


Figure 8: Comparison of damage pattern by extensive spalling near the corners in the experiment and in the numerical analysis.

4. Examples

4.1 Identification of Material Parameters

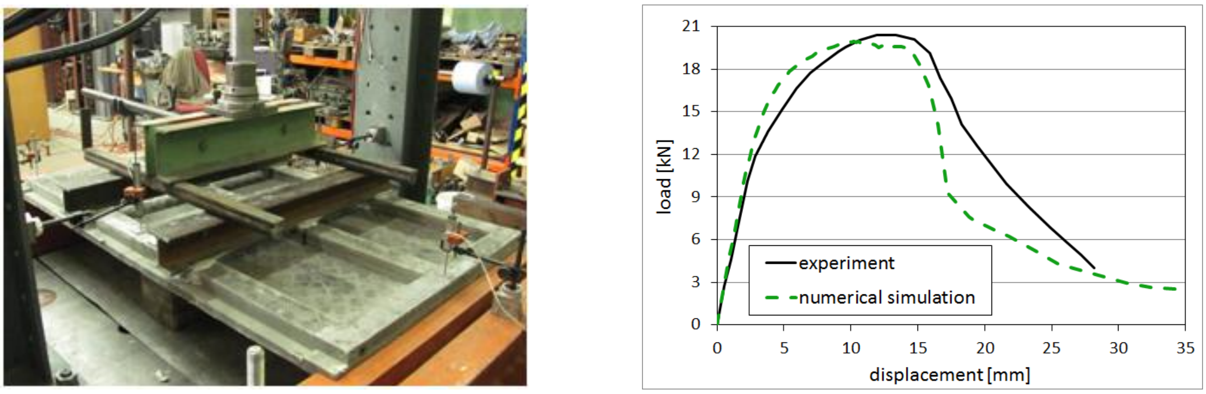
It is necessary to determine FRC material parameters to successfully model FRC structures in programme ATENA. In this case, material corresponding to the class C110/130 and reinforced with the steel fibres in volume fraction 1.5 % is chosen. Parameters for the numerical model are determined by inverse analysis of the laboratory results four-point bending tests. Material model 3D NLC2 User is used for modelling in program ATENA [9].



(a) (b)

Figure 9: (a) Softening curves, (b) Comparison of experimental results and numerical simulations of four-point bending tests

For the inverse analysis, software Consoft developed by Slowik et al. [10] is applied. Automatic analysis based on the evolutionary algorithms is used for the determination of cohesive law function. The best results of inverse analysis are shown in Figure 9. Softening curves for two material models are shown in the Figure 9a, comparison between numerical and experimental results is shown in the Figure 9b. The results of numerical simulations are in a perfect accordance with the experimental results. Material model 3D NLC2 User with softening curve derived by the inverse analysis was validated by the numerical simulation of four-point bending tests of bridge slabs used for reconstruction of a bridge in Czech Republic; they should serve as a permanent formwork [11]. Load bearing capacity of the model is pretty close to the experiment and the fracture of the slab occurred also in accordance with the experiment in the transverse direction approximately at the edge of loading plate.



(a) (b)

Figure 10: (a) Four-point bending test of slab, (b) Comparison of experimental and numerical results

4.2 Application Example – Tunnel Tubbing

Two examples of fibre reinforced concrete structural elements are presented in this chapter and afterwards used for extending study of safety concepts in chapter 2.3. The first example is a four point bending beam (see Figure 11).

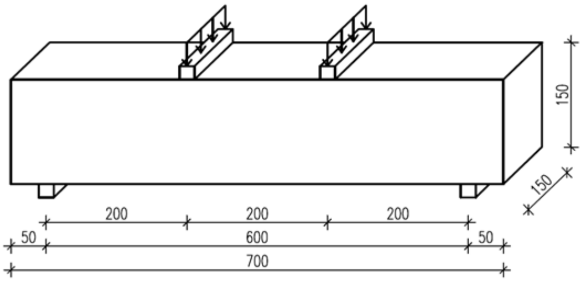
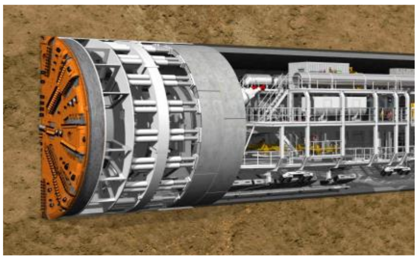


Figure 11: Geometry of the FRC bending beam



(a)

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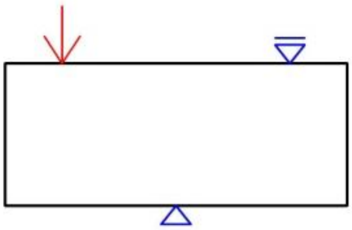
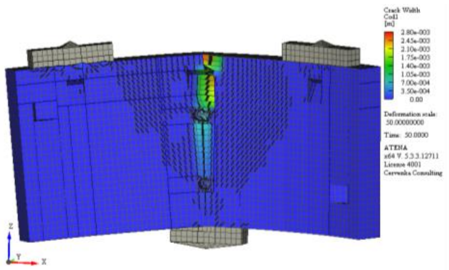


(c)



(d)

Figure 12: Case study example of a tunnel tubing made of fibre reinforced concrete

The mean material parameters were first calibrated by inverse analysis described in the previous chapter and then the global safety approaches were used to calculate the corresponding design resistances. The second example represents a tunnel lining segment (see Figure 12a) installed by TBM (tunnel boring machine) during tunnel excavation. Full size laboratory tests of both RC and SFRC segments have been performed [12] in the Klokner Institute of CTU in order to check their resistance under various loading conditions. This experimental and analytical program was part of an engineering project in Prague, Czech Republic [13]. Maximum load measured in experiments with SFRC segments was around 500 kN. The numerical model was first validated by experimental data for a loading scenario simulating the action of the TBM machine during the installation and assembly of segments (see Figure 12b, c, d). After that the global safety formats above were applied to calculate the design resistance (Figure 4), see chapter 2.3.

4.3 Synthetic and Steel fibres in prestressed, precast long span beams

4.3.1 Test specimens

Four large-scale, prismatic, prestressed, T-shaped beams with 19 m span were produced: two with synthetic fibres and two with steel fibres. The height of the beam was 90 cm, the width of the flange was 50 cm, and the web thickness was 14 cm. Concrete was C50/60-XC1-16, but the first test was made only at 19 days after casting. The homogeneity of the strength was measured by Schmidt hammer.

Six stirrups were placed in the web (height is 45 cm, not reaching the flange), in one meter from the edge of the element to avoid spalling stresses due to the release of the prestressing force, but shear reinforcement was substituted by the fibres. Before the tests 10-40 cm long cracks with 0.05-0.3 mm width were appeared 45-50 cm from the soffit. There were 15-45 cm long cracks with 0.1 mm width between the web and the flange.

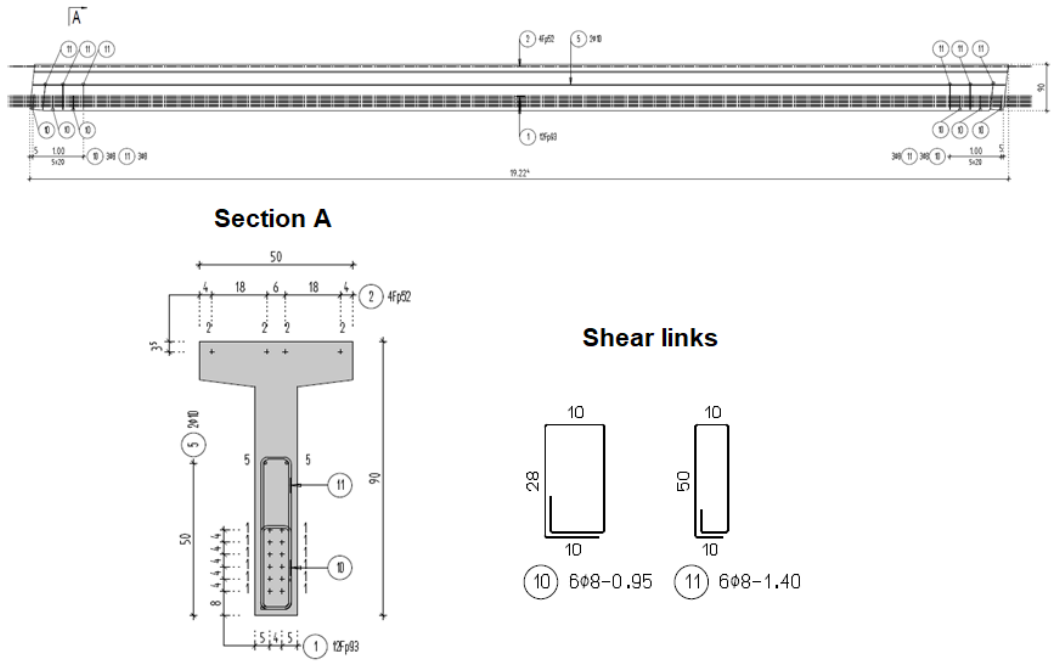


Figure 11: Geometry of the beam

4.3.2 Laboratory tests

Four point bending test were made to model the built-in behaviour of the beams. The loads were acted in each one-fifth point of the span to be similar to the real load distribution. Force, deflection in the middle of the span, crack patter was recorded in fifteen load-steps. It was decided after reaching the 130% of the design value of the bending resistance, loading will be stopped without a break-off failure to remain the beam-end uncracked for shear tests. A crack with 1.0 mm width was declared failure.

Shear load was affected ~2.5h distance from the beam-end and it was increased until failure. Test and pictures were made by ÉMI-TÜV SÜD Kft.

Figure 12: Spalling crack in the end of the beam

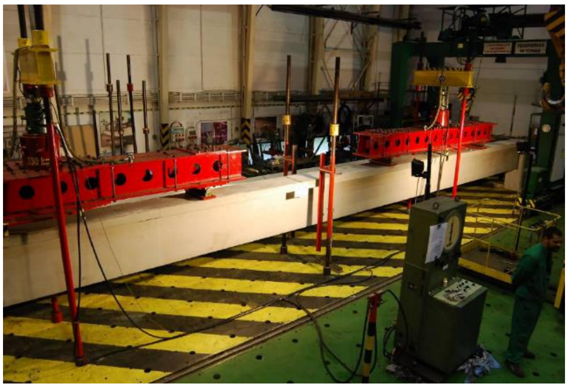


Figure 13: Bending (left) and shear (right) tests

4.3.3 Results for Bending Beams

Beams made of steel and synthetic fibre reinforced concrete showed similar load bearing behaviour during bending tests. Cracks appeared regularly and frequently between the two outside press, the beam end remained uncracked. As the load was increased, cracks started to open and reached the flange. Cracks with 1.0 mm width were appeared at 120% of the design value of the bending resistance, but they closed due to the high prestressing force after deloading.

Figure 14: Failure of the element

In case of synthetic fibres the crack propagation process started earlier, at lower loading level, was faster and cracks were closer to each other. In the seventh load step inclined (~45°) cracks appeared at the outside loads. In case of steel fibres the same was observed only in tenth. After two loading level their width was the same as pure bending cracks'. Other new cracks' inclination was lower. In the last loading level they reached 1.0 mm width. Failure was observed at the shear-bending zone with obvious prognostic in both cases.

4.3.4 Results for Shear Beams

In the shear tests first cracks appeared at 115% of the design value of the shear resistance. Failure with 1.0 mm width was observed at 200%, the break off was at 230%. All the cracks went from the support to the load, the firsts' inclination was 35-45°, and the last was 18°. Failure was ductile in cases of both steel and synthetic fibres.


Figure 15: Bending (left) and shear (right) tests

Figure 16: Cracked surface of the element

4.3.5 Material Model of the Concrete and FRC

The effect of the fibre in the concrete was investigated in previous grandstand concrete elements at the new stadium in Debrecen, Hungary. Four point beam test were made on 150 mm x 150 mm and 550 mm long beams, according to RILEM TC162. After the results, inverse analysis was made and the correct added fracture energy was measured by fibre dosage. Modified fracture energy is a new and simple way to model the behaviour of FRC in tension and bending. The crack-width diagram was defined until 4 mm crack opening as a limit from an engineering point of view.

The finite element model used the following material parameters for fibre reinforced concrete:

- Elastic modulus: 37GPa
- Tensile strength: 4.1 MPa

- Compressive strength: 58MPa
- Poisson ratio: 0.2
- Residual flexural strength: 0.97 MPa
- Fracture energy of the concrete: 0.103 kN/m

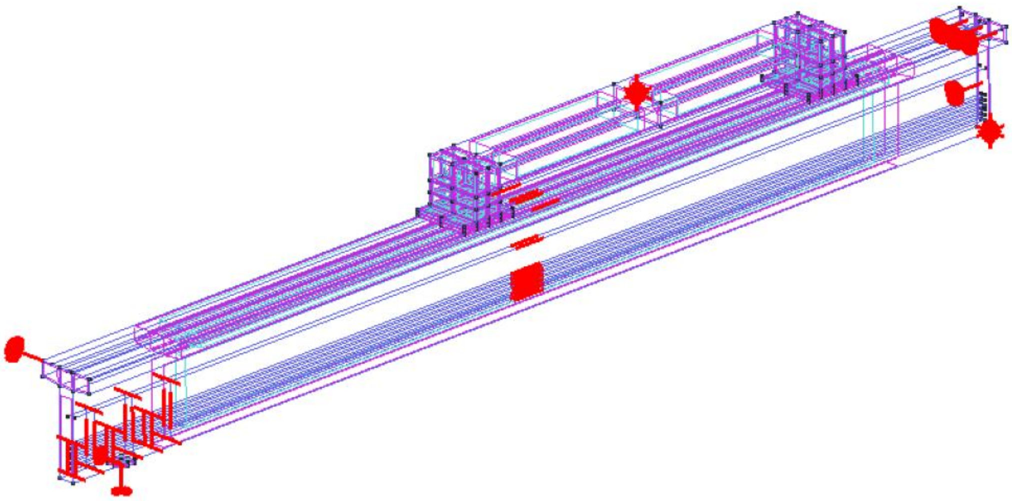


Figure 17: Simplified model in Atena finite element program

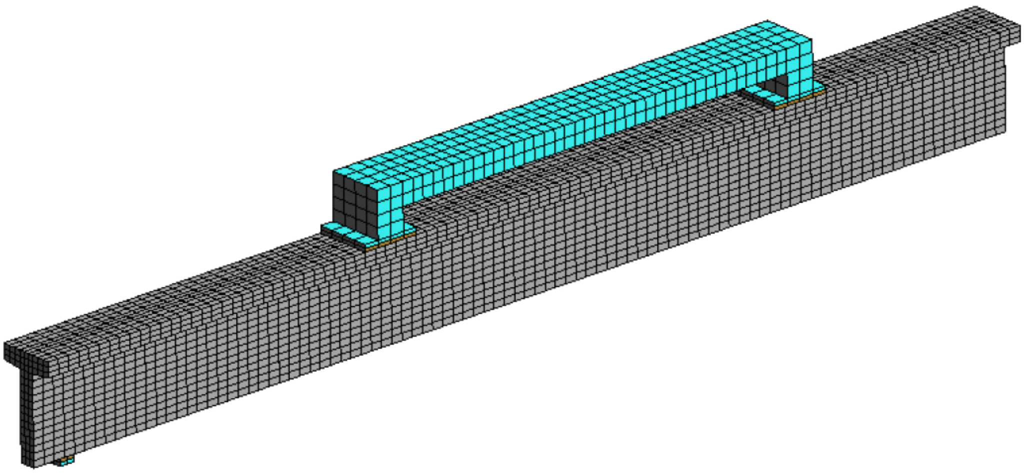


Figure 18: Structural mesh in Atena finite element program

4.3.6 Numerical and Test Results

The numerical calculation shows good correlation with the test result. The fibre reinforced concrete beam has the maximum bending capacity 52% higher than the plain concrete one.

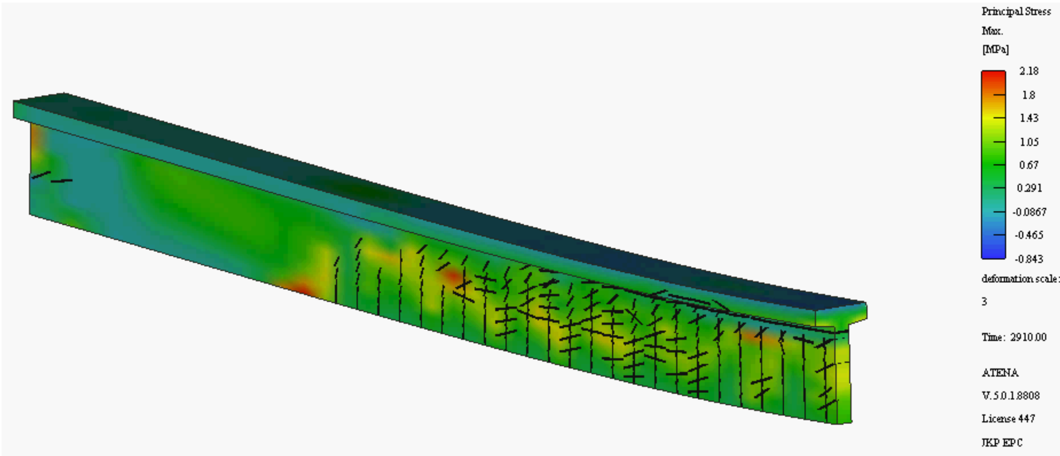


Figure 19: Principal stresses and cracks in Atena finite element program

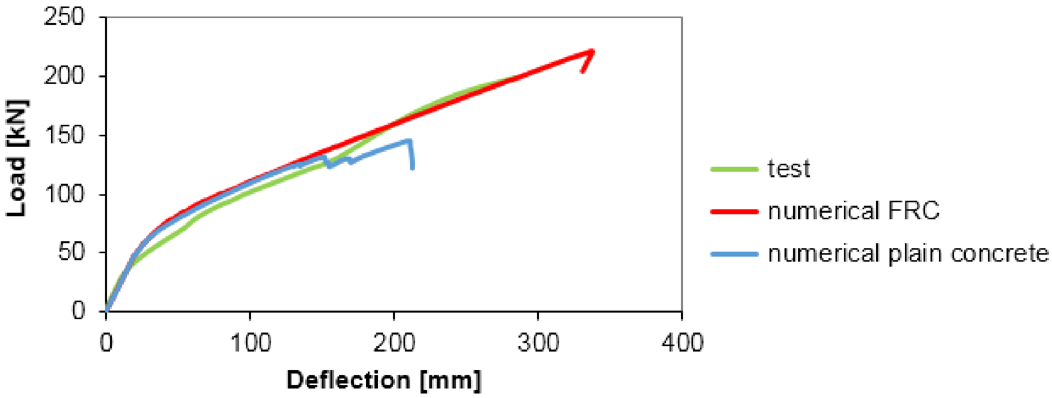


Figure 20: Test and numerical load-deflection results

4.3.7 Conclusion

The structural behaviour was clear, but advanced statistical analysis cannot be performed due to the limited number of beams. The existence of horizontal spalling cracks on the beam ends was predicted by the verified finite element analysis. Calculation shows higher dosage of fibres or extra reinforcement is needed to avoid spalling failure, although these cracks do not influence the load bearing capacity of the beam.

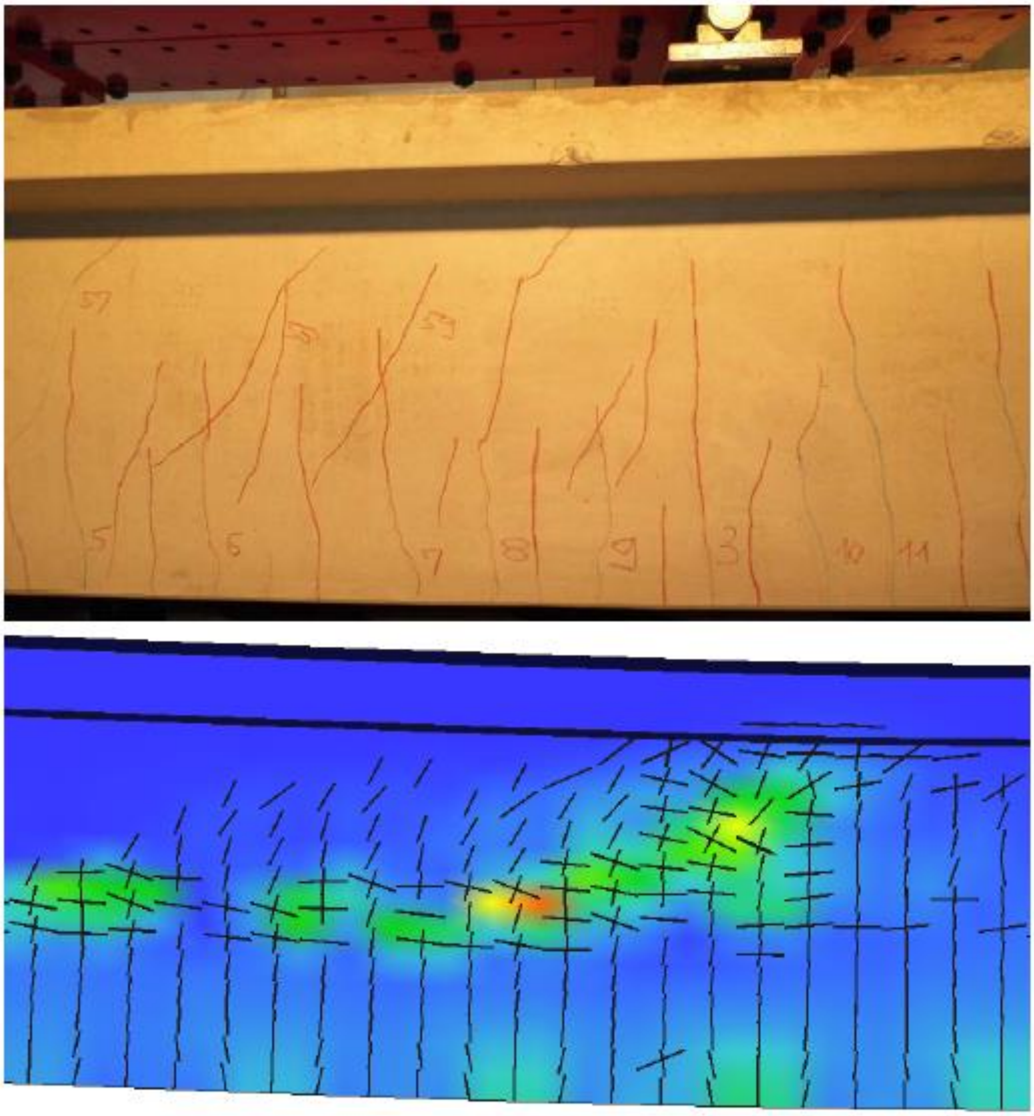


Figure 21: Test and numerical crack propagation

There was no difference between steel and polymer fibre reinforced concrete beams in load bearing capacity. In the four-point bending test failure occurred in the bended-sheared area by inclined cracks, although the crack-width in the pure-bended zone was also remarkable. Inclined shear crack with 1.0 mm width was achieved at the same load level in the two cases. Breaking shear load was 25% higher, showing tough behaviour. Breaking was ductile with obvious prognostic. The cracked surface was examined, the fibres mostly pulled out instead of tearing. Finite element analysis shows significantly higher (52%) load bearing capacity of the fibre reinforced beam compared to plain concrete one.

4.4 Prestressed reinforced concrete grandstand reinforced with synthetic macro fibre

Current case aims of assess the predictive performance of FEM-based model for the analysis of a prestressed FRC stadium's grandstand. This assessment is performed by taking results obtained in a laboratory test with a scale precast R/FRC stadium's grandstand [16] reinforced with synthetic macro fibre. This is a real scale precast R/FRC stadium's grandstand. Due to the complex geometry of the grandstand, manufacturing and positioning of the shear stirrups is costly, therefore the use of short fibres was explored for the total replacement of steel stirrups as a shear reinforcement. To avoid injuries in the spectators due to eventual exposition of steel fibres in the external surface of these type of structural elements, synthetic macro (polypropylene, PP) fibre were selected for the shear reinforcement.

4.4.1 Laboratory tests

Based on a comparative experimental test program, the PP fibre type that ensured the highest average residual strength up to 3.5 mm crack width was chosen. For this comparison, beams were manufactured with the same dosage and the same concrete but with different PP fibre types. The chosen PP fibre was 48 mm long and embossed surface, with a modulus of elasticity of 12 GPa and a tensile strength of 640 MPa. Another experimental program was executed with beams of C40/50 concrete strength class reinforced with this selected PP fibre, by using fibre dosages of 2.5, 5 and 10 kg/m^3 in order to characterize the post-cracking tensile behaviour of these FRCs. From the obtained results it was estimated, by interpolation, the tensile performance of FRC reinforced with 2.5 kg/m^3+ΔD_f, up to 10kg/m^3, with ΔD_f=0.5 kg/m^3.

The grandstand was simulated by considering the following load cases: 1) loaded in the whole standing area; 2)loaded only in the lower standing level; 3) loaded in the upper standing level; 4) loading and unloading; and 5) dynamic loading. Load combinations and safety factors were used according to the Eurocode.

Material parameters of the fibre reinforcement were defined by inverse analysis using the results from three point notched bending beam test according to the recommendations of MC2010. The finite element model was loaded by displacement control exactly how the real tests were carried out.

4.4.2 Material Model of the Concrete and FRC

Material parameters – concrete mean values, concrete strength class: C30/37

- Young's modulus: 32 GPa
- Poisson coefficient: 0.2
- Tensile strength 2.9 MPa
- Compressive strength 38 MPa
- Fracture energy 0.073 N/mm
- Aggregate interlock activated, dmax: 20mm
- Plastic strain 0.00119

Material parameters – FRC

- Added fracture energy, G_{Ff} 2.7 N/mm

Material parameters – tendon

- Young modulus 195 GPa
- Characteristic yield strength 1860 MPa
- Yield strength 2046 MPa
- Initial prestressing 865 MPa

4.4.3 Numerical and Test Results

6 real-size elements were made, from which 4 were macro fibre-reinforced and 2 were made without fibre reinforcement, but with traditional shear stirrup reinforcement. Bending and shear tests were made under laboratory conditions. Elements were loaded on both stairs continuously, loads, deflection (vertical displacement: in front of and in the back of the element in the middle and in both ends; horizontal displacement: only in the middle of the grandstand) and crack patterns were recorded. Results show all of the elements met the requirements specified (at SLS: maximum deflection of l/250, maximum crack width of 0.3 mm) and carried the load in the same way.

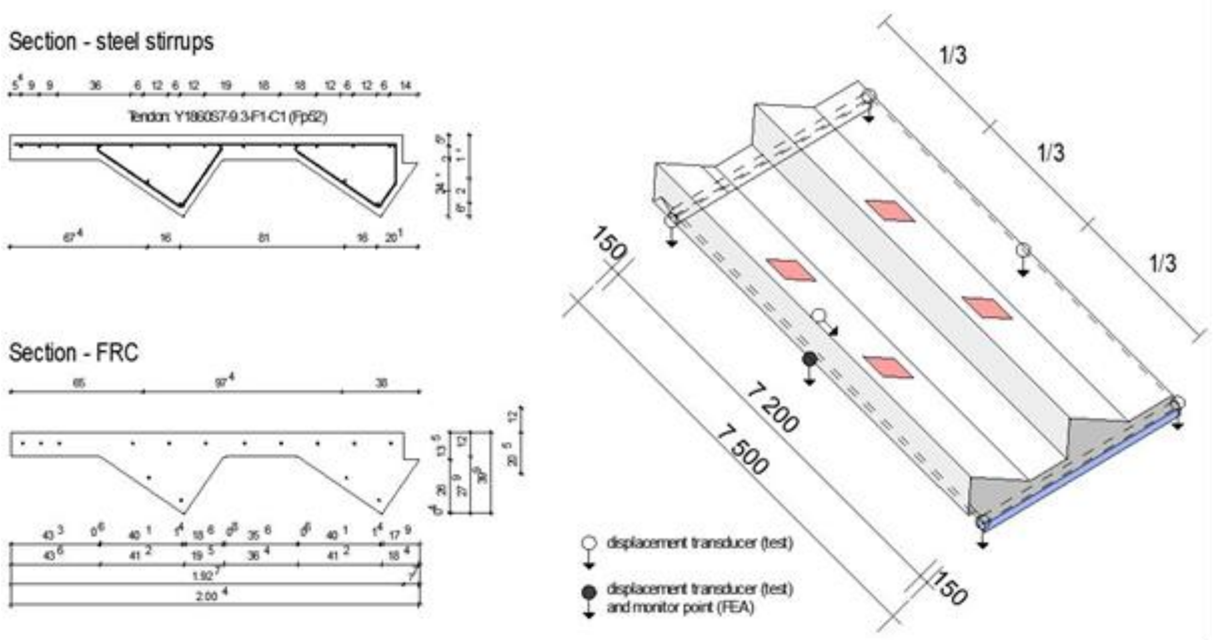


Figure 22: cross section (left) laboratory setup (right)

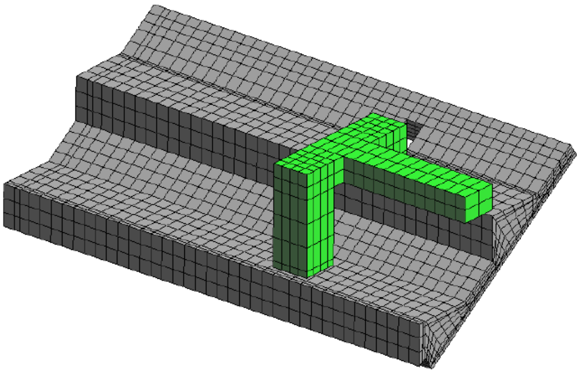


Figure 23: Laboratory test (left) numerical model (right)

Numerical results fit the real test results well, thus further finite-element calculations were made with different dosages. The optimal dosage defined was therefore 3 kg/m^3.

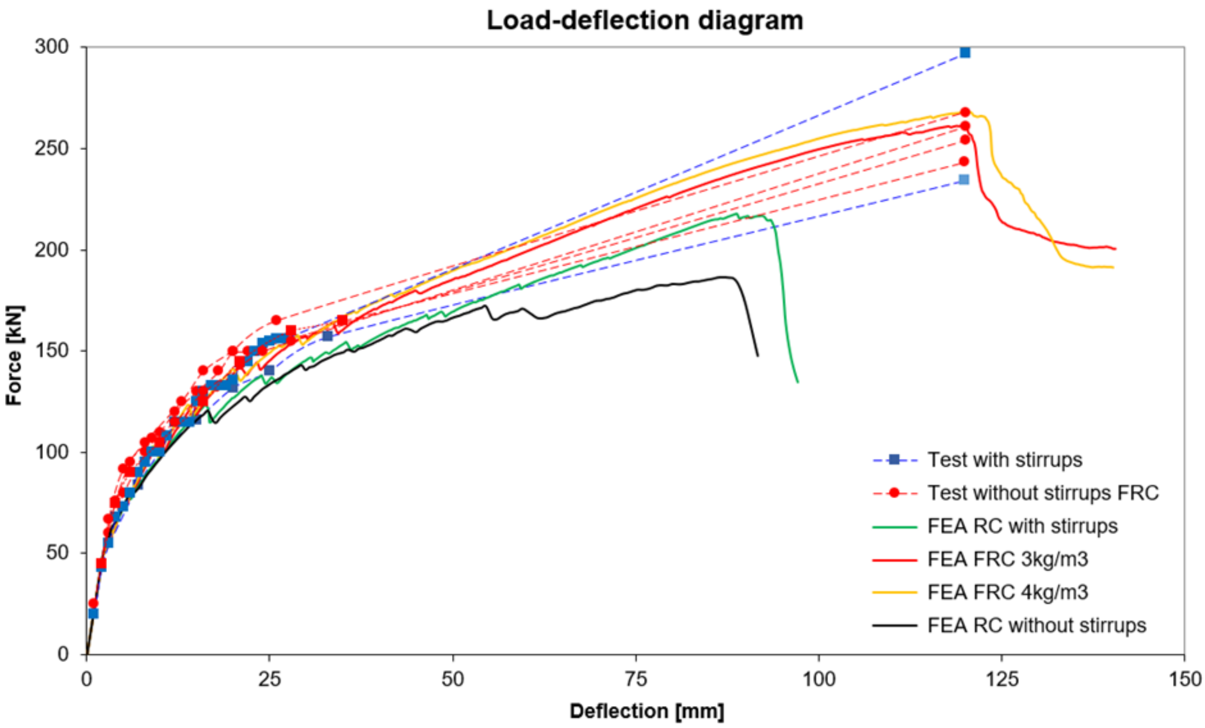


Figure 24: Load and deflection diagram of test and FEA

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