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The influence of continuing reinforcement on the load capacity of a RC beam previously exposed to high temperatures

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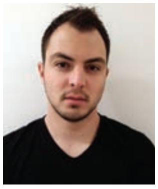

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Preliminary note

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The influence of continuing reinforcement on the load capacity of a RC beam previously exposed to high temperatures

The paper describes the RC beam model development and the influence exerted by the main longitudinal reinforcement overlapping and transverse reinforcement (ties) on the bearing capacity of a RC load bearing structure for several cases of load, with an emphasis on the influence of high temperatures. Several RC beam models are made and relevant calculations and results are presented, which show the influence of the reinforcement method on the bearing capacity of structures, i.e. of the main-reinforcement continuing as related to the one-part reinforcement, as well as the influence of transverse reinforcement (ties).

Key words:
RC beam, main reinforcement continuing and overlap, concrete damage, cracks, high temperatures

Prethodno priopćenje

Krešimir Ninčević, Joško Ožbolt, Ivica Boko

Utjecaj nastavljanja armature na nosivost ab grede prethodno izložene djelovanju visokih temperatura

U radu je opisana izrada modela ab grede i istraživanje utjecaja preklapanja glavne uzdužne armature i utjecaj poprečne armature (spona) na nosivost ab nosive konstrukcije za više slučajeva opterećenja, s naglaskom na utjecaj djelovanja visokih temperatura. Napravljeno je više modela ab grede te su prikazani proračuni i rezultati iz kojih je vidljiv utjecaj načina armiranja na nosivost konstrukcije, odnosno nastavljanja glavne armature u odnosu na armaturu iz jednog dijela, kao i utjecaj poprečne armature (spona).

Ključne riječi:
ab greda, nastavljanje glavne armature i preklapanje, oštećenje betona, pukotine, visoke temperature

Vorherige Mitteilung

Krešimir Ninčević, Joško Ožbolt, Ivica Boko

Einfluss von Bewehrungsstößen auf die Tragfähigkeit von Stahlbetonbalken nach der Einwirkung hoher Temperaturen

In dieser Arbeit werden Modelle von Stahlbetonbalken und entsprechende Untersuchungen von Stössen der Hauptarmierung in Längsrichtung sowie der Einfluss der Querbewehrung (Bügel) auf die Tragfähigkeit von Stahlbetonkonstruktionen für mehrere Lastfälle beschrieben, wobei der Schwerpunkt auf Einwirkungen hoher Temperaturen gelegt wird. Es wurden mehrere Modelle erstellt und die Berechnungsvorgänge dargestellt. Aus den Resultaten ist der Einfluss der Bewehrungsführung, bzw. der Fortführung der Hauptarmierung, sowie der Querarmierung (Bügel) auf die Tragfähigkeit der Konstruktion ersichtlich.

Schlüsselwörter:
Stahlbetonbalken, Bewehrungsfortführung, Bewehrungsstösse, Betonbeschädigung, Risse, hohe Temperaturen

1. Introduction

The behaviour of reinforced concrete structures exposed to fire and high temperatures, with observation of the damage and usability rating of structures during and after the effects of such types of load, is currently considered to be one of the main and highly topical research issues worldwide. Understanding behaviour of reinforced concrete structures during and after exposure to fire, with simultaneous exposure to continuous and moving load, is very important for the safe and rational sizing of structures. In the first place, it is important to understand the behaviour and characteristics of certain materials forming the load bearing structure (concrete, steel...), as well as their interaction. The development of simple and efficient numerical models that take into account the effects of high temperatures, especially if these models have been confirmed by experimental tests, forms the basis for a more detailed study of stochastic processes, such as fire and consequences of its actions on load bearing structures, and for further updating of standards and regulations so as to enable more efficient and safer design of structures. Most of today's regulations and standards provide rather simplified approach and guidelines related to dimensioning and resistance to fire activity. The standards and regulations used in this paper are listed in [2-4]. It should be noted that obstacles in the observed structure present a problem, because most regulations are based on the behaviour of simple static systems. In reality, such a simple bearing element is a part of a continuous beam and structure, which can cause unexpected behaviour and response of the structure. Extensive fire tests conducted in 1995-1996 [5] show that a static system, as part of a bearing structure, can have significantly higher fire resistance than when considered as a separate static system. Although it is known that, in comparison to other materials, reinforced concrete structures exhibit a relatively good behaviour during fire or high temperatures, it should be observed that, after the effects of such load, changes in the initial characteristics of material occur, i.e. significant features of structural materials are affected [6, 7]. The occurrence of these degradation mechanisms causes damage to the load-bearing structure during and after fire, which results in a reduced bearing capacity of the reinforced concrete structure [8], as well as in mechanical and temperature damage to concrete [9, 10].

The paper shows results of numerical analysis aimed at determining behaviour of a reinforced concrete beam at high temperatures and various loads, i.e. for beam load without the action of fire and high temperatures, and for beam load after exposure to fire. The modelling and geometrical characteristics of the reinforced concrete beam are based on the paper by Ožbolt et. al. [7], where a similar static model of reinforced concrete beam, loaded at four points by bending, was studied. Unlike the concept presented in paper [7], the objective of this paper is to study the effect of different reinforcing methods on the load-bearing capacity of structures after previous simulation of fire activity and material degradation as a result of high temperature. The modelling of all RC beam models presented in this paper, i.e. insertion of model geometry, description of material characteristics, and loading and analysis of these models, was performed using computer programmes FEMAP® and MASA (*Macroscopic Space Analysis*) [11]. The finite-element computer programme MASA is used for non linear calculation and analysis of three dimensional (3D) finite elements of structures made of quasi-fragile materials, such as concrete, stone, ceramics, etc. Although different types of materials can be analysed, the programme is mostly intended for non-linear analysis of concrete and reinforced concrete in the framework of the continuum mechanics theory, taking into account damage of material [7, 12, 13, 14], e.g. cracking of concrete or flow of reinforcement. The programme can be used to analyse and solve mechanical problems, i.e. to conduct static and dynamic analyses of load-bearing structures. It may also serve for solving non-mechanical problems, such as the analysis of transport processes in porous media, analysis of corrosion on a reinforced concrete structure, or analysis of fire action and exposure to high temperatures. The knowledge and understanding of such computer programmes enable creation of different models and loads, i.e. prediction of behaviour of load-bearing structures and response to actual load in real environment and time. This kind of research is still much cheaper compared to creation of prototypes and conduct of physical tests and experiments on real elements. The finite-element analysis aims to reduce the time and cost required for development and improvement.

2. RC beam modelling

A thermo-mechanical model [7, 12, 15, 16] of the reinforced concrete beam, loaded at the mid span of the girder, was developed for the purpose of this testing, using the three-dimensional (3D) finite element method. The thermo-mechanical model is required so as to simulate response of the load-bearing structure after degradation of mechanical properties due to high temperature effects. A more detailed description of the thermo-mechanical model is presented in paper [7]. This model ensures that mechanical properties of materials (concrete) depend on the temperature, while temperature distribution is not dependent on such properties. Concrete was modelled using the so-called planar micro model [17], while a plastic model served for reinforcement by applying von Mises criterion [18]. The so-called "Crack band" regularization method was applied to make sure that results are not dependent on the size of finite elements [19].

The computer programme FEMAP® is used for preparing input data and for analysing finite-element results after calculation. The program allows us to use the finite-element method to generate nodes and connect them to create a network of finite elements. It also allows us to set boundary conditions of the model, to define various ways of loading, and to select and describe various materials. The load setting method is incremental, i.e. it is divided into a number of steps, depending on the force or predetermined increments.

2.1. Geometrical properties of structural member

The reinforced concrete beam is rectangular in cross-section and measures 4.0 m in total span, while its dimensions are b/h = 200/300 mm. It is reinforced in the upper and lower zones with rod-shaped reinforcement 12 mm in diameter, i.e. by four rods in the lower zone and two rods in the upper zone and by ties 10/200 mm in diameter. The concrete cover is 26 mm in thickness. Due to complexity of the model and to simplify calculation, as well as to reduce the total number of finite element networks (shorter calculation time), a quarter of the model was developed, because the symmetry of the model itself provides such possibility. The model of the simulated beam is rectangular in cross section and measures 2.0 m in span, while its dimensions are b/h = 100/300 mm, as shown in Figure 1.

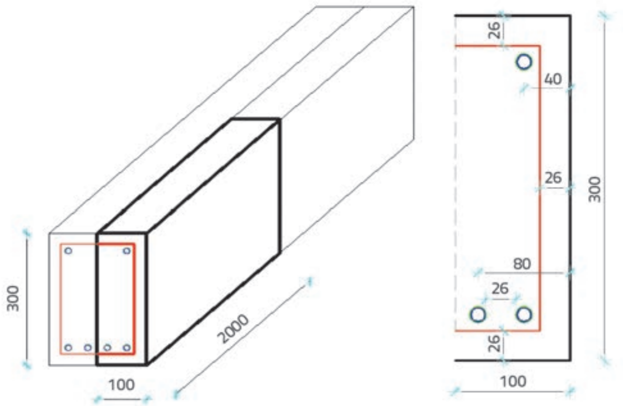

Figure 1. Beam model with corresponding cross section

The main longitudinal reinforcement is modelled as a solid body made of three-dimensional (3D) finite elements, while the ties (transverse reinforcement) are dimensioned as one-dimensional elements (bar elements). For realistic modelling of reinforcement splicing details, the bars should fully be modelled by 3D finite elements. The 3D elements allow realistic description of stress state in the zone of reinforcement splicing: bond, radial and tangential stresses in concrete around the reinforcement. Such stress states can not be described realistically using common bar elements. Transverse reinforcement (ties) can be modelled using bar elements, because this modelling is sufficient for simulation of lateral adherence which the ties provide. It is not realistic to model the connection between the ties and the main reinforcement by fixed connection, because in reality the ties are not welded to main reinforcement, but are only held in place. Therefore, in this paper they are modelled separately from the main reinforcement. The main longitudinal reinforcement in the overlap zone is modelled in the same way. Main reinforcement anchoring (at the end of the reinforced concrete beam) is modelled so that the concrete elements at the end of the reinforcement are assigned linear properties, and as such they actually simulate hooks. A 1 mm thick layer of elements, called contact elements, is modelled around longitudinal reinforcement. Contact elements serve only for modelling the surface zone between concrete and steel reinforcement, or to simulate connection at the contact of two materials, and can transfer the shear and compressive stress only. Three-dimensional elements with eight nodes and eight integration points (hexahedron three-dimensional (3D) finite elements HexMesh solids) are used for spatial discretization of steel (reinforcement, contact elements, and steel plates). The transverse reinforcement (consisting of steel ties) is modelled by means of one-dimensional bar elements.

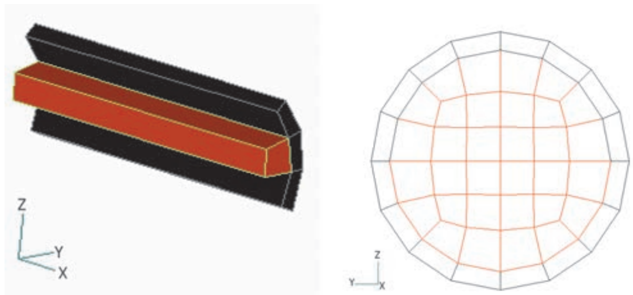

Figure 2. Finite element of reinforcement and contact element

Spatial discretization (network) of finite elements of concrete consists of tetrahedral three-dimensional (3D) finite elements with four nodes and four integration points, as shown in Figure 3.

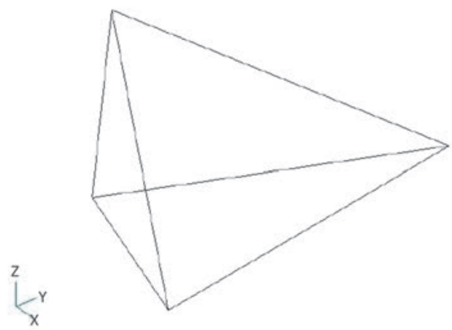

Figure 3. Tetrahedral finite element of concrete (four-node element)

The biggest 20 mm tetrahedral element of concrete is defined when specifying the number of elements by each model geometry line, or when modelling the finite element network of concrete. It is very important to devote enough time to modelling such networks of tetrahedral and hexahedral three-dimensional finite elements, in order to avoid mistakes and gain more realistic results. For successful creation of the finite element network, it is necessary to control that all finite elements (tetrahedral and hexahedral) interconnect (continue) in their nodes only.

The dimensions of reinforcing bars forming the main longitudinal reinforcement are 2 x 1000 mm and 2 x 1600 mm for the simulated beam 2 m in span, Figure 4. The diameter of all longitudinal reinforcing bars is 12 mm, while ties are 10 mm in diameter. The overlap of longitudinal reinforcement in the tension zone is 600 mm (50 x Ø [mm]). The minimum length of overlap necessary to ensure the transfer of force from one rod to another, prescribed by HRN EN 1992 ($l_0 = \alpha_1\ \alpha_2\ \alpha_3\ \alpha_5\ \alpha_6\ l_{b,rqrd} \geq l_{0,min}$), was reduced by

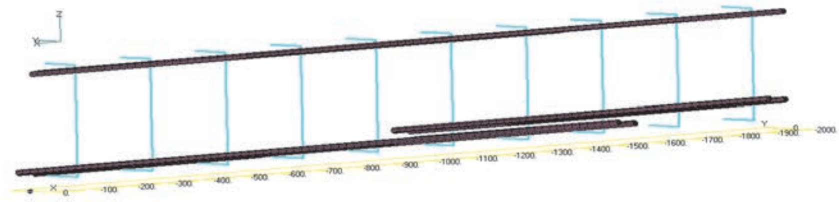

Figure 4. Longitudinal and transverse reinforcement of reinforced concrete beam

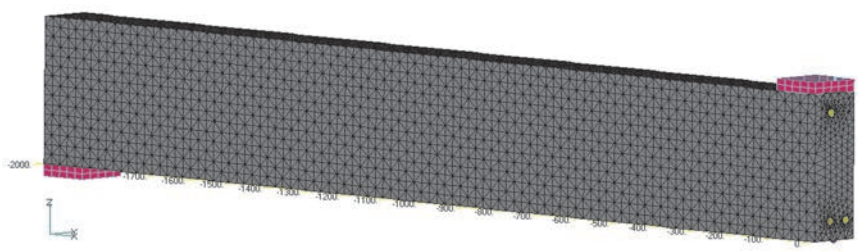

Figure 5. Finite element networks for RC beam (half span)

30 % in this study. Two steel plates were modelled to simulate real conditions. One of them was placed at the bottom at the beginning of the beam, at the position of the bearing, and the other was placed in the centre of the beam. Its role was to better assume and transfer the load, but also to avoid possible local damage to concrete during application of load, Figure 5. Steel plate dimensions are 100/100/25 mm.

2.2. Reinforcement models

The analysis was conducted for several distinct models of similar geometrical characteristics, but differing in the form of reinforcement:

- reinforced concrete beam with one-part longitudinal reinforcement in the bottom tension zone and with transverse reinforcement (ties), as shown in Figure 6
- reinforced concrete beam with two-part longitudinal reinforcement in the lower tension zone (reinforcement overlap), and with transverse reinforcement (ties), as shown in Figure 7
- reinforced concrete beam with two-part longitudinal reinforcement in the lower tension zone (reinforcement overlap), but without transverse reinforcement (ties), as shown in Figure 8.

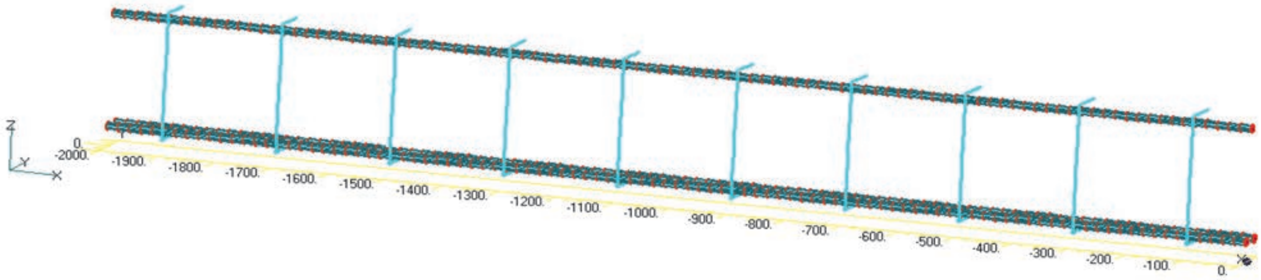

Figure 6. Reinforcement according to first model

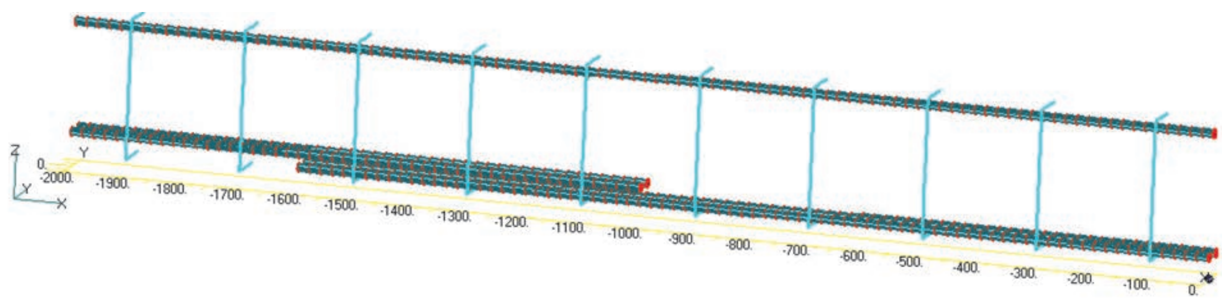

Figure 7. Reinforcement according to second model

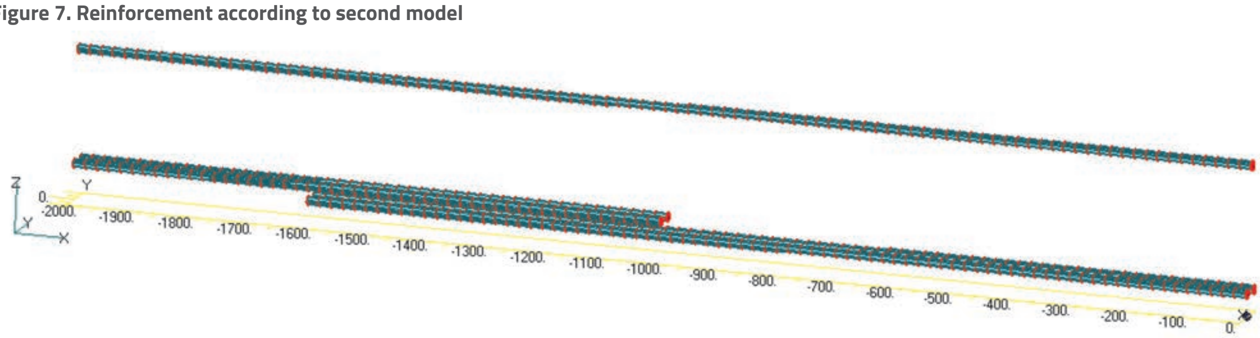

Figure 8. Reinforcement according to third model

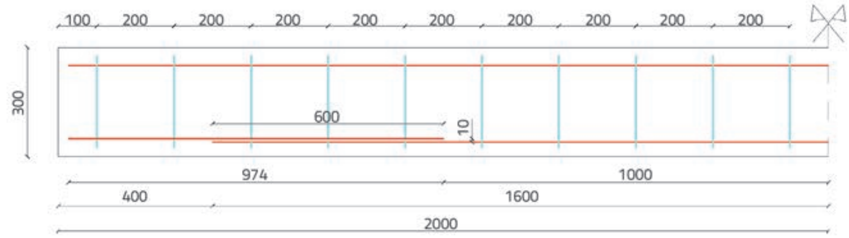

Figure 9. Sketch of reinforcement plan

For simplicity reasons, detailed results will be given only for the model of reinforced concrete beam with two-part longitudinal reinforcement in the lower tension zone (overlapping reinforcement) and transverse reinforcement (ties), and a table with calculation results will be shown for all models in conclusion.

Note: The distribution of ties is equal in the first and the second models, and the main longitudinal reinforcement in the tension zone is equal in the second and third models. The main longitudinal reinforcement in the pressure zone is equal for all models, Figure 9.

2.3. Material characteristics of reinforced concrete beam

Temperature dependence of the planar micro model is described so that the macroscopic properties of concrete (Young's modulus, compressive and tensile strength, and energy fracture) are variable due to elevated temperatures, based on experimental data [7, 13, 14], Figures 10, 11, and 12. The reinforced concrete beam with the following characteristics of concrete is analysed:

- characteristic compressive strength of f_{ck} = 25.0 MPa
- tensile strength f_t = 2.0 MPa
- Young's elasticity modulus E_c = 28000 MPa
- Poisson's ratio ν = 0.18
- fracture energy G_F = 0.08 N/mm.

Experiments show that mechanical properties of steel change and are subject to changes at elevated temperatures [20]. This phenomenon is taken into account in the model through application of reduced diagrams for the yield point of steel and

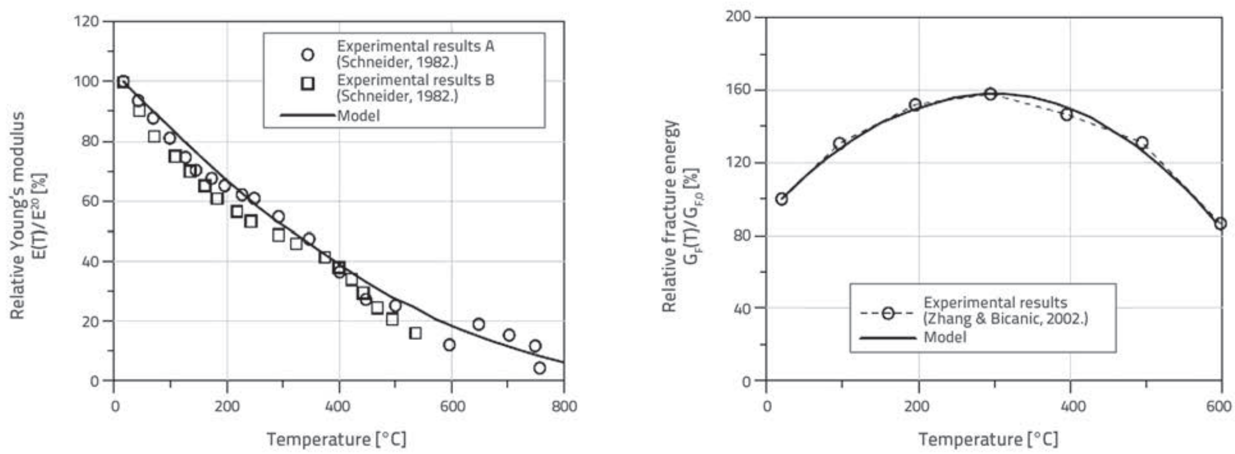

Figure 10. Young's elasticity modulus and energy of fracture of concrete as related to temperature [7, 13, 14]

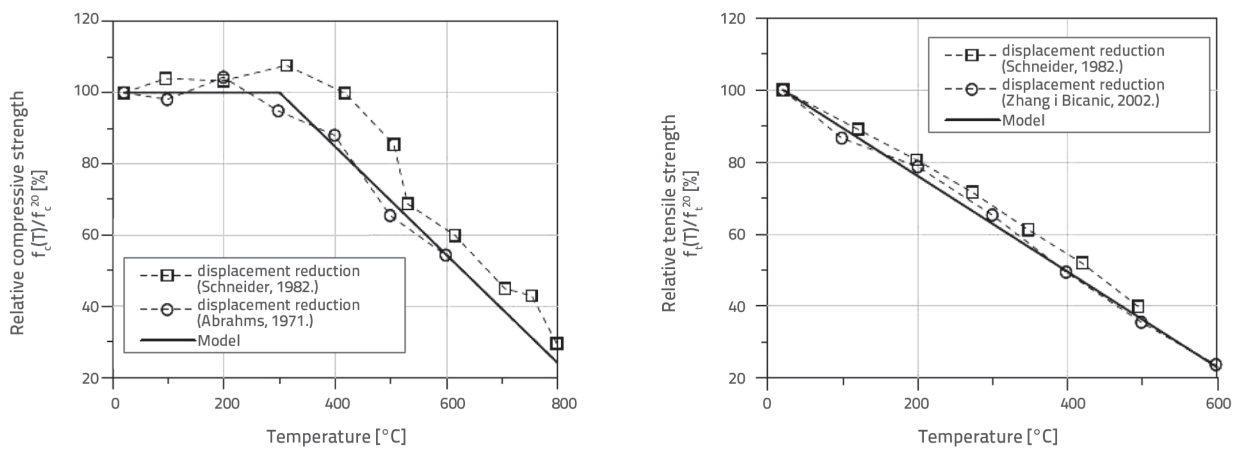

Figure 11. Compressive and tensile strength of concrete as related to temperature [7, 13, 14]

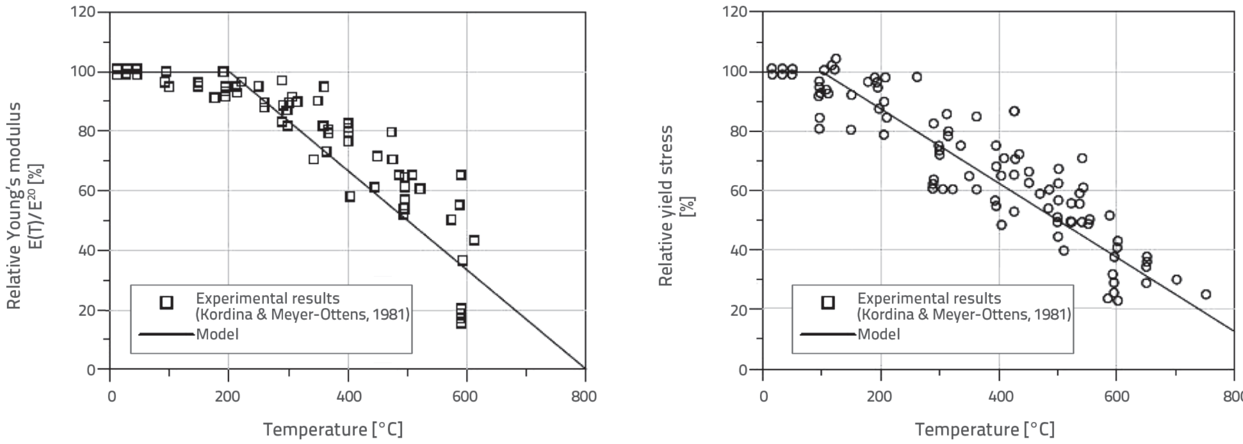

Figure 12. Young's elasticity modulus and yield strength of steel as related to temperature [7, 13, 14]

Young's elasticity modulus, as shown in Figure 12. Although these two characteristics are reduced due to high temperature, experiments show that yield point of steel can be restored, unlike that of concrete where degradation of material is irreversible [21]. The longitudinal and transverse reinforcement exhibits the following characteristics:

- yield strength f_y = 480 MPa
- tensile strength f_u = 580 MPa
- Young's modulus of elasticity E = 210 000 MPa
- Poisson's ratio ν = 0.33

3. Application of load

Two basic ways of applying load were used in the analysis of reinforced concrete beams:

- load by controlled displacement at the centre of the beam (incremental procedure)
- high temperature load and fire simulation (beam heated from three sides).

Two groups of model tests were established for model loading. In the first group, load was applied to the model only by displacement and the bearing capacity was monitored until collapse. The second group is a combination of the two loads, which means that all models were originally exposed to high temperatures and simulation of fire, cooled to the desired temperature according to the specified heating and cooling protocol, and then subjected to displacement load in order to check bearing capacity (Figure 13).

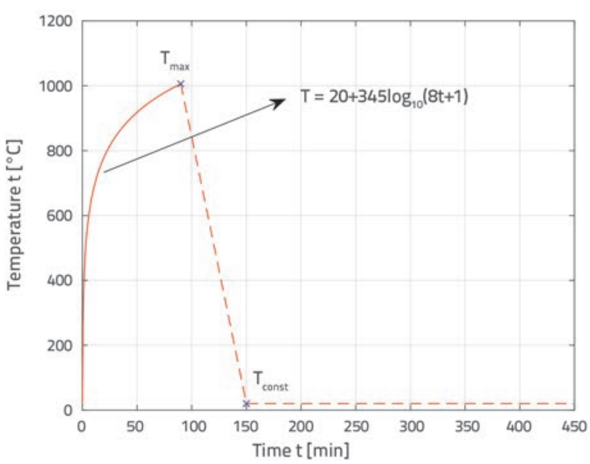

Figure 13. Heating (according to ETK curve) and cooling protocol used

The ISO-834 curve (standard fire curve) [4] was adopted as temperature load. The temperature of the fire-affected area increased in the first 30 minutes to 850 °C, and in the next 90 minutes to about 1050 °C.

4. Temperature distribution in reinforced concrete beam

For simplicity reasons and due to very similar results of temperature distribution in reinforced concrete beams, the temperature analysis is restricted to a single model of reinforced concrete beam, with continuous longitudinal reinforcement of the lower tensile zone (overlapping reinforcement) and transverse reinforcement (ties), as shown in Figures 14 to 21.

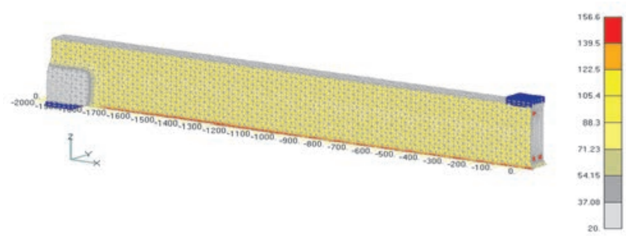

Figure 14. Temperature distribution in concrete beam after 5 minutes

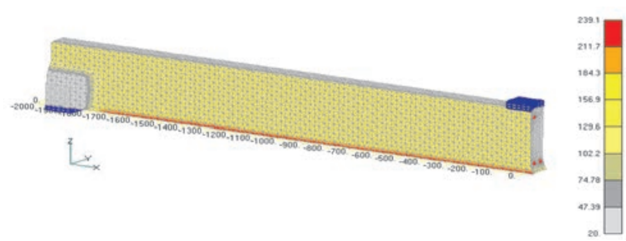

Figure 15. Temperature distribution in concrete beam after 10 minutes

The analysis of temperature field in the beam shows that after 5 minutes, or between 5 and 10 minutes, a significant temperature rise is registered in peripheral elements of the beam, particularly at the lower edge of the beam (the beam is heated from the external and bottom sides).

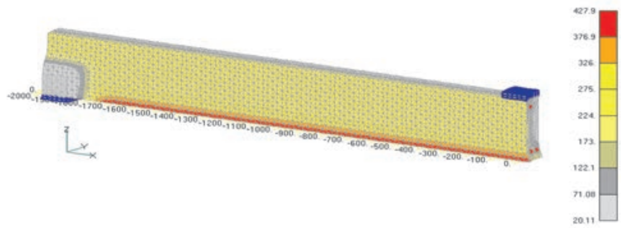

Figure 16. Temperature distribution in concrete beam after 30 minutes

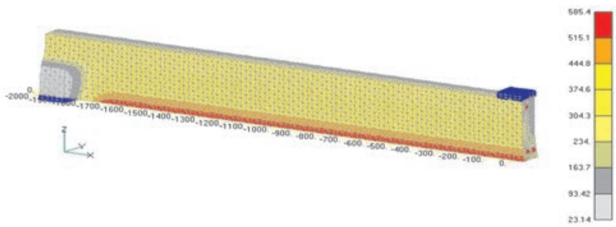

Figure 17. Temperature distribution in concrete beam after 60 minutes

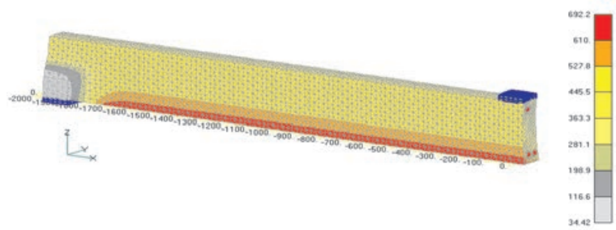

Figure 18. Temperature distribution in concrete beam after 90 minutes (end of heating and start of cooling)

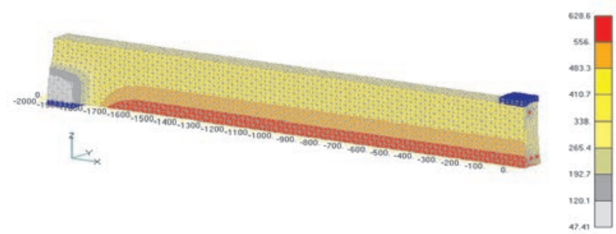

Figure 19. Temperature distribution in concrete beam after 110 minutes

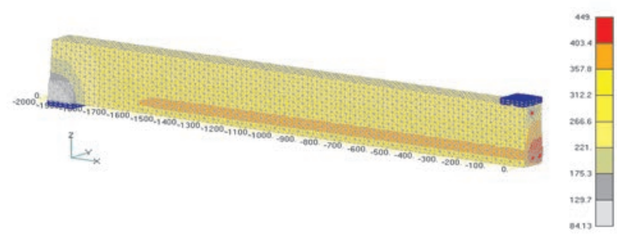

Figure 20. Temperature distribution in concrete beam after 150 minutes (end of linear cooling and start of constant cooling)

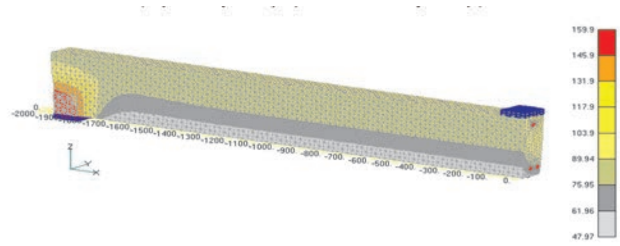

Figure 21. Temperature distribution in concrete beam after 450 minutes (end of cooling process)

Figure 22 shows temperature distribution in the reinforced concrete beam after the end of heating and cooling, and the state of the beam immediately before loading by displacement until collapse. The temperature gradient shown in the figure reveals that 300 minutes of cooling is not sufficient for reaching room temperature over the entire cross section of the beam. Concentration of elevated temperature at the left part of the beam above the support can be explained by heat accumulation and anchor modelling, as concrete elements above the support are modelled as elastic elements and were not exposed to heating and cooling. Temperature distribution values for various periods are realistic, as confirmed by other similar investigations [5, 6, 7, 20].

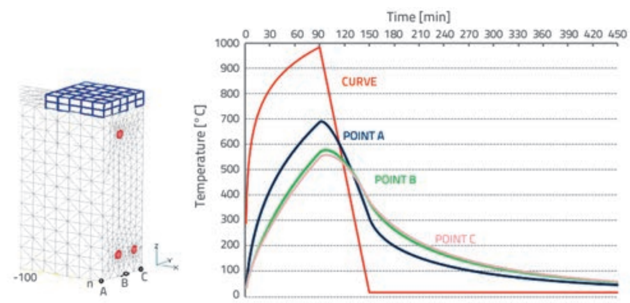

Figure 22. Points used for temperature distribution and heating and cooling curves

5. Presentation and comparison of results

Two groups of model tests were established for model loading. In the first group, load was applied to the model only by displacement and the bearing capacity was monitored until collapse. The second group is a combination of the two loads, which means that all models were originally exposed to high temperatures and simulation of fire, cooled to the desired temperature according to the specified heating and cooling protocol, and then subjected to displacement load in order to check bearing capacity Therefore, all test and calculation results, and their comparison, will be presented in the conclusion. Figures 23 to 27 show detailed results of reinforcement stress and concrete damage for only one model of reinforced concrete beam, with two-part longitudinal reinforcement in the lower tension zone (overlapping reinforcement) and transverse reinforcement (ties).

Note for Figures 23 to 30:
LEFT SIDE - models subjected to displacement load only;
RIGHT SIDE - models exposed to displacement load after being

subjected to high temperatures and cooling. The range of displayed stresses in reinforcement can vary from 0 to 480 N/mm^2. The main tensile stress (cracks) in concrete is shown by relative deformation in the range from 0.0 to 0.10, where deformation of 0.01 corresponds to the crack width of 0.2 mm for the average length of finite element of 20 mm. Cracks formed in concrete after the tensile strength was exceeded. According to the limit state of cracks in RC structures, the critical crack width is w_g=0.3 mm.

It can be seen from the shown state of stress in RC beam ties that there was no flow of reinforcement, and that maximum strength was not exceeded, even immediately before the fracture and failure of the structural member.

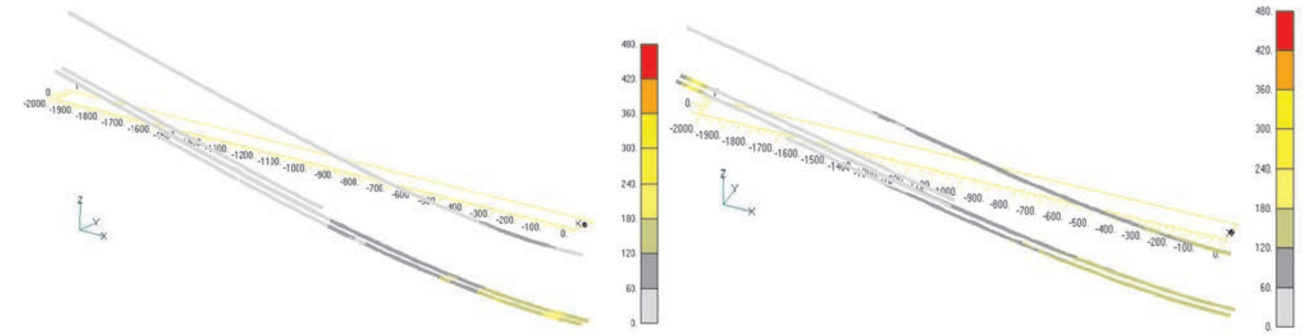

Figure 23. Stresses in main longitudinal reinforcement for 6 mm displacement

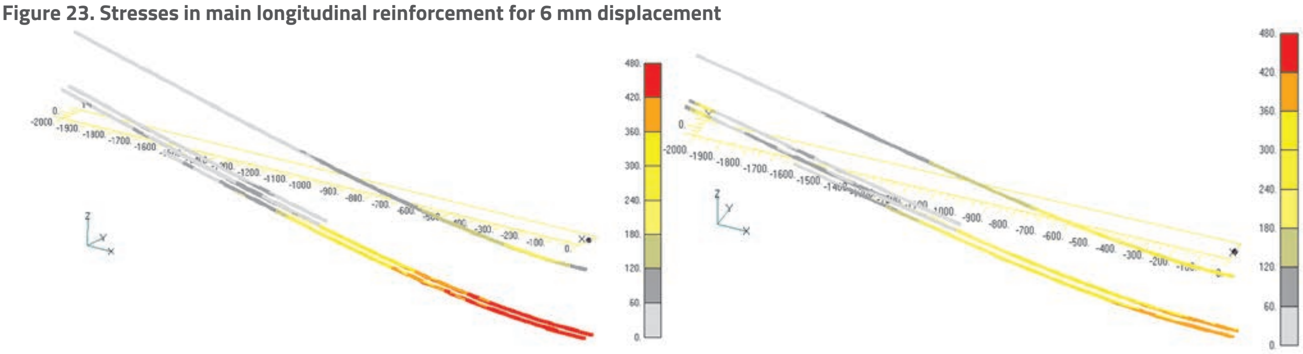

Figure 24. Stresses in main longitudinal reinforcement for 21 mm displacement

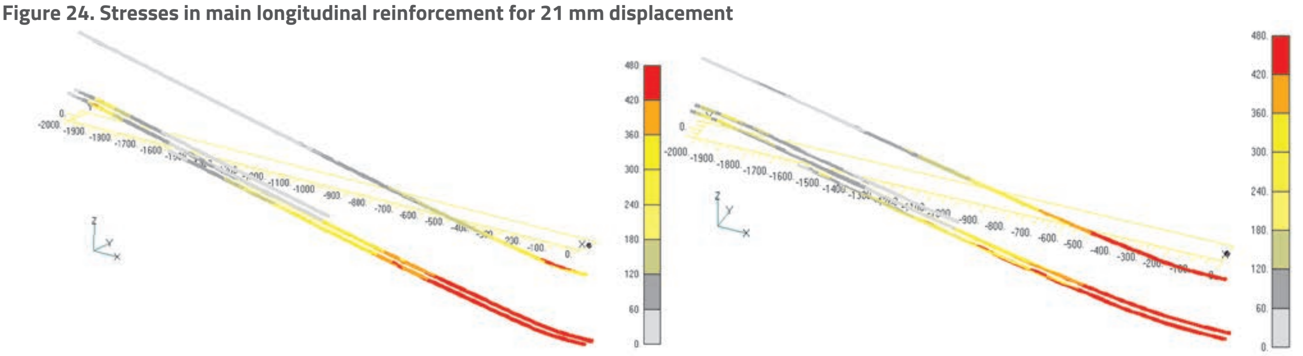

Figure 25. Stresses in main longitudinal reinforcement for 81 mm displacement

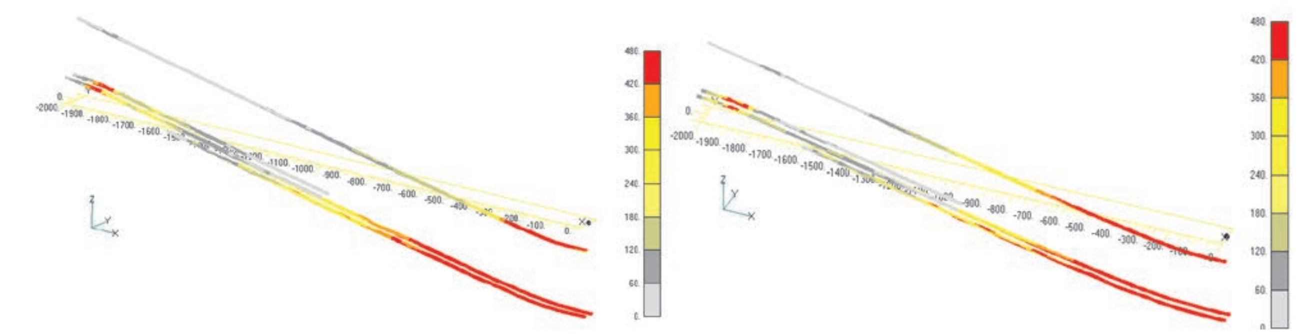

Figure 26. Stresses in main longitudinal reinforcement immediately before bearing capacity failure (left displacement of 154 mm, displacement to the right by 144 mm)

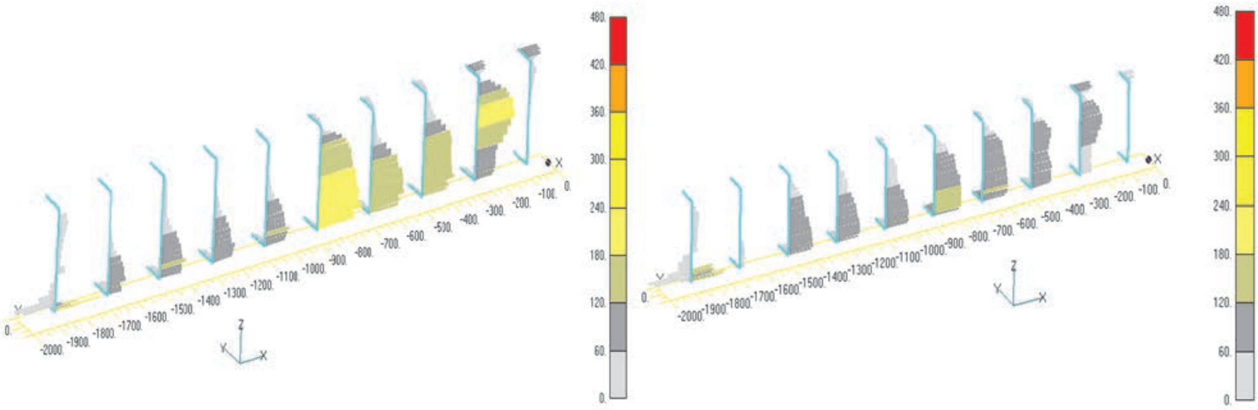

Figure 27. Stresses in ties immediately before bearing capacity failure (left displacement of 154 mm, displacement to the right by 144 mm)

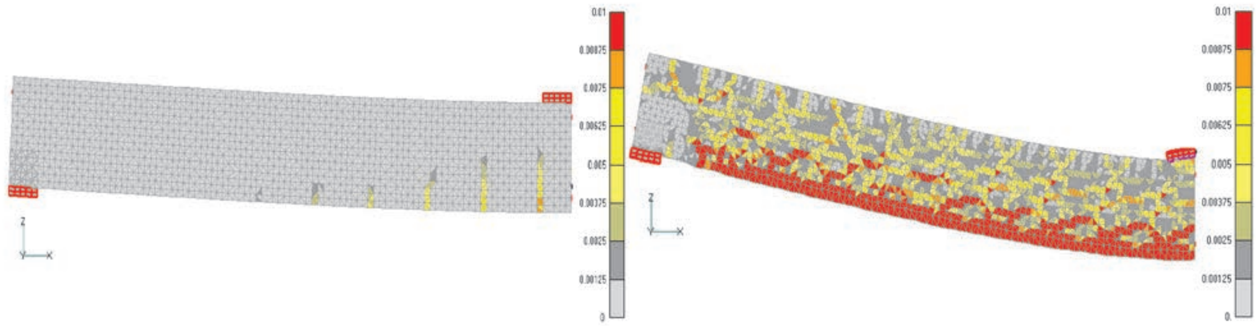

Figure 28. Damage to concrete and cracks at 6 mm displacement

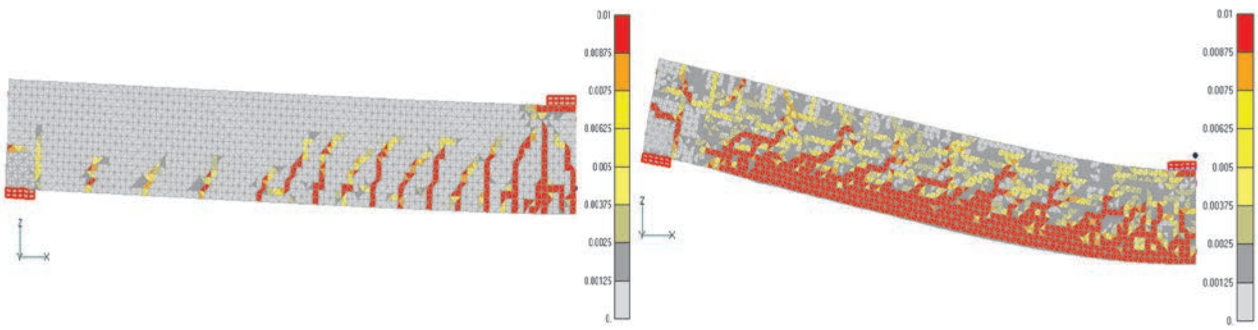

Figure 29. Damage to concrete and cracks at 51 mm displacement

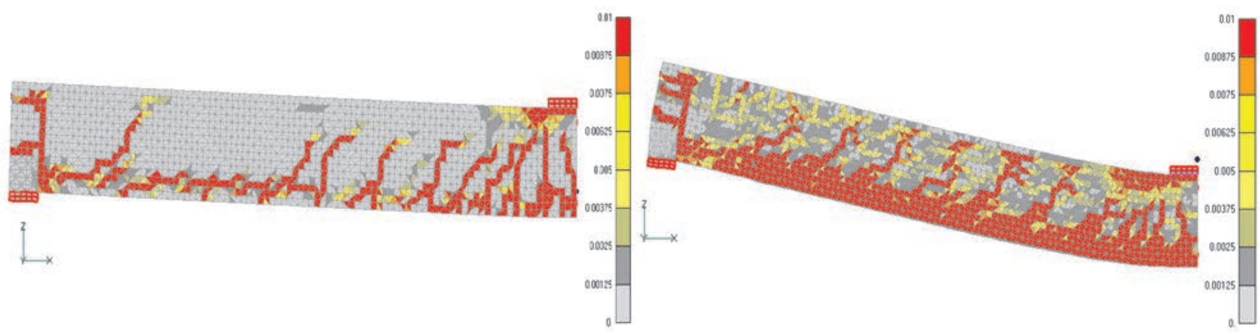

Figure 30. Damage to concrete and cracking immediately before failure (left displacement: 154 mm, right displacement: 144 mm)

The peeling of the protective layer of concrete occurs due to the heating and cooling of the reinforced concrete beam, as can be seen in Figures 28 to 30 to the right, and as confirmed in other studies [6, 7]. The nonuniform degree of heating, and temperature gradient through cross-section of the RC element, result in temperature strain and stress, which leads to peeling and damage of concrete. Greater exposure to high temperature causes major damage to concrete, as well as additional damage during cooling. Water found in concrete starts to change its physical state at the temperature of 105°C. Further temperature increase causes cement dehydration. The destruction of cement gel occurs at temperatures between 800 and 900°C. The behaviour of concrete at high temperatures also depends on the type and mineralogical composition of aggregate, because of possible loss of water in the aggregate, and change of properties.

6. Comparison of all RC model results

Figures 31 to 35 show all forms of RC beam bearing capacity. As can be seen in Figures 31 to 35, the bearing force of the reinforced concrete beam for the model that was exposed to high temperature prior to loading by displacement, is lower due to damage to concrete during fire action. However, immediately before the failure of the RC beam, the displacement is in this case considerably bigger.

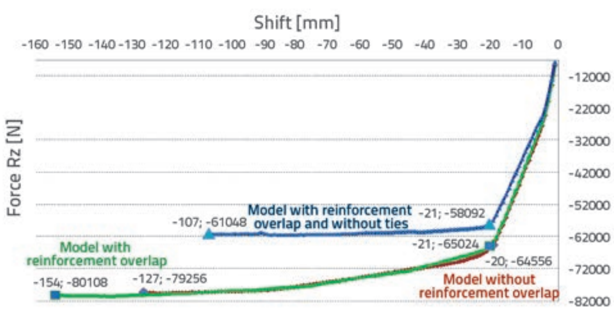

Figure 31. Bearing capacity diagrams (displacement - force) of reinforced concrete beams subjected to displacement load only

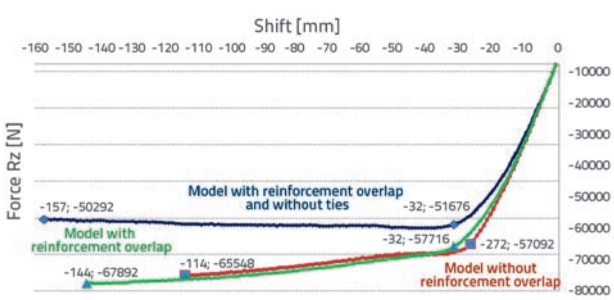

Figure 32. Bearing capacity diagrams (displacement - force) of reinforced concrete beams subjected to displacement load after exposure to high temperatures and cooling

This can be explained by the fact that compressive stresses are also generated inside the reinforced concrete due to heating, e.g. in the direction of the longitudinal axis of the beam, and these stresses influence fracture energy of concrete, which increases and hence contributes to the increase in ductility of the beam.

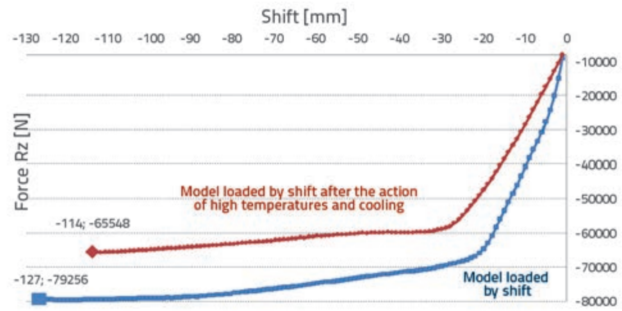

Figure 33. Bearing capacity diagrams (shift-force) of reinforced concrete beam with one-part longitudinal reinforcement

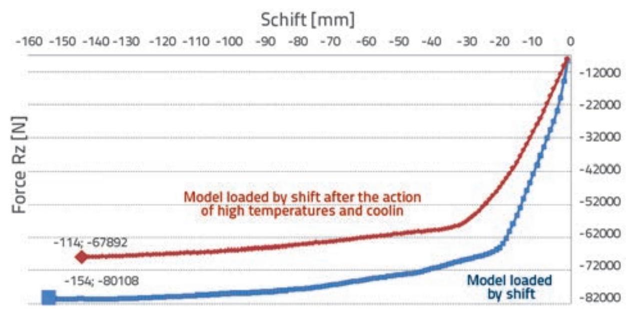

Figure 34. Bearing capacity diagrams (displacement-force) of the RC beam with overlapping longitudinal reinforcement

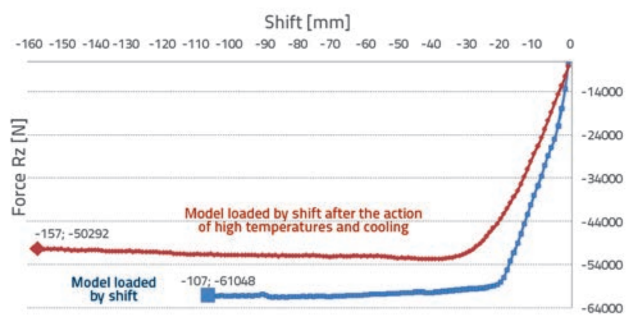

Figure 35. Bearing capacity diagrams (displacement-force) of the RC beam with overlapping longitudinal reinforcement, without transverse reinforcement (ties)

Note: *Concrete beam experiments show that fracture energy increases with an increase in temperature and, after the temperature of about 400 °C is exceeded, the beam begins to fail, which confirms the said occurrence and reasons.*

Table 1. Table of calculation results for all models

Numerical results			
MODELS	**Displacement load**	**Temperature + displacement load**	
	displacement [mm] / force [N]	displacement [mm] / force [N]	Force reduction [%]
1. MODEL	127 / 79256	114 / 65548	**17.3**
2. MODEL	154 / 80108	144 / 67892	**15.2**
3. MODEL	107 / 61048	157 / 50292	**17.6**

7. Conclusions

The tests and calculation results presented in the paper show that the expected damage and degradation of the reinforced concrete beam material was caused by high temperature and fire simulation, and by a significant decline in bearing capacity. The comparison of the two models reveals the influence of different ways of reinforcing using longitudinal reinforcement in the lower tension zone. The model with the main longitudinal overlapping reinforcement exhibits a considerably larger displacement immediately before failure in the numerical model, while the final force value is slightly higher. The reason for such slight increase in force can be explained by the fact that the reinforcement overlapping zone is closer to the bearing than to the zone of impact of maximum moments. The consequence of reinforcement overlapping is an increased share of steel in RC beam and a higher reinforcement coefficient. This results in an increased ductility (toughness) of structural elements and hence in greater displacement. Ductility is important as a means of avoiding sudden demolition of a structure due to load expected during the life and use of the structure. Higher ductility means higher deformability in nonlinear field. Tests have also shown the impact of transverse reinforcement, i.e. significant decline of bearing capacity can be observed in the model without transverse reinforcement (ties). Such an outcome is quite expected because the observed model is a statically determined system, i.e. a freely supported simple beam, subjected to vertical displacement load.

All described tests were performed on the presented numerical models and their results are used to predict the behaviour and response of the bearing structure or structural member subjected to load testing in real time and environment. However, the number of these and other experimental studies is still insufficient for production of more reliable and accurate test results, which is mostly due to difficult working and measurement conditions under the effect of high temperature, and to high cost of testing.

REFERENCES

[1] Ninčević, K.: Utjecaj nastavljanja armature na nosivost i oštećenje betona armiranobetonske grede prethodno izložene djelovanju visokih temperatura, diplomski rad, Fakultet građevinarstva, arhitekture i geodezije, Sveučilište u Splitu, 2014.

[2] EN 1992-1-2:2010. Part 1.2 design of concrete structures. Structural fire design.

[3] IS 456:2000. Indian standard plain and reinforced concrete – code of practice. Bureau of Indian Standards, New Delhi; 2000.

[4] CEB-FIP bulletin 46. Fire design of concrete structures–structural behaviour and assessment. Federation internationale du beton (fib); 2008.

[5] Swinden Technology Centre, The Behaviour of multi-storey steel-framed buildings in fire: A European joint research programme, British Steel plc, Rotherham, UK, 1999.

[6] Sharma, A., Bošnjak, J., Ožbolt, J., Hofmann, J.: Numerical modeling of reinforcement pull-out and cover splitting in fire-exposed beam-end specimens, Engineering Structures, 111 (2016), pp. 217-232, https://doi.org/10.1016/j.engstruct.2015.12.017

[7] Ožbolt, J., Bošnjak, J., Periškić, G., Sharma, A.: 3D numerical analysis of reinforced concrete beams exposed to elevated temperature, Engineering Structures, 58 (2014), pp. 166–174, https://doi.org/10.1016/j.engstruct.2012.11.030

[8] Albrifkani, S., Wang, Y.C.: Explicit modelling of large deflection behaviour of restrained reinforced concrete beams in fire, Engineering Structures, 121 (2016), pp. 97-119, https://doi.org/10.1016/j.engstruct.2016.04.032

[9] Kodur, V.K.R., Agrawal, A.: An approach for evaluating residual capacity of reinforced concrete beams exposed to fire, Engineering Structures,110 (2016), pp. 293-306, https://doi.org/10.1016/j.engstruct.2015.11.047

[10] Hakan, E.: Predicting the moment capacity of RC beams exposed to fire using ANNs, Construction and Building Materials, 101 (2015) 1, pp. 30-38, https://doi.org/10.1016/j.conbuildmat.2015.10.049

[11] Ožbolt, J.: *MASA-Macroscopic Space Analysis*, User Manual, Internal Report, Inst. of Constr. Mat., University of Stuttgart, Germany, 1998.

[12] Ožbolt, J., Kožar, I., Eligehausen, R., Periškić, G.: Instationares 3D thermomechanisches modell fur Beton, Beton Stahlbetonbau, 100 (2005) 1, in German, https://doi.org/10.1002/best.200590006

[13] Schneider, U.: Properties of materials at high temperatures, concrete. 2nd ed. RILEM technical committee 44-PHT. Kassel: Technical University of Kassel, 1986.

[14] Zhang, B., Bićanić, N.: Residual fracture toughness of normal- and high-strength gravel concrete after heating to 600 _C. ACI Mater, 99 (2000), pp. 217–26.

[15] Borst, R., Peeters, P.P.J.M.: Analysis of concrete structures under thermal loading. Comput Method Appl Mech, 77 (1989) 3, pp. 293–310, https://doi.org/10.1016/0045-7825(89)90079-0

[16] Luccioni, B.M., Figueroa, M.I., Danesi, R.F.: Thermo-mechanic model for concrete exposed to elevated temperatures. Eng Struct, 25 (2003), pp. 729–742, https://doi.org/10.1016/S0141-0296(02)00209-2

[17] Ožbolt, J., Li ,Y.J., Kožar, I.: Microplane model for concrete with relaxed kinematic constraint. Int J Solids Struct, 8 (2001), pp. 2683–2711, https://doi.org/10.1016/S0020-7683(00)00177-3

[18] Von Mises, R.: Mechanik der festen Körper im plastisch deformablen Zustand, Göttin. Nachr. Math. Phys., 1 (1913), pp. 582–592.

[19] Bažant, Z.P., Oh, B.H.: Crack band theory for fracture of concrete. RILEM, 983 (2016) 93, pp.155–77.

[20] Kordina, K., Meyer-Ottens, C.: Beton brandschutz handbuch, Dusseldorf, Verlag Bau+Technik, 1981.

[21] Takeuchi, M., Hiramoto, M., Kumagai, N., Yamazaki, N., Kodaira, A., Sugiyama, K.: Material properties of concrete and steel bars at elevated temperatures. In: SMiRT 12; 1993.