ANALYSIS OF REINFORCED CONCRETE BEAMS SUBJECTED TO IMPACT LOADING

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Abstract

The utilisation of complex nonlinear material models for concrete in numerical simulations is necessary for the accurate representation of structural behaviour. However, the successful modelling of such complex behaviour depends on a good understanding of the material model parameters.

This paper deals with the critical issue of material parameter sensitivity in the context of RC beams subjected to impact loading.

The objective was to establish relationships between the material parameters and the responses, including deformations and stresses, using sensitivity. This is the main key to understanding the complex interaction of these parameters and their influence on the structure.

Keywords

Reinforced concrete beam, numerical simulations, impact loading, nonlinear material models, sensitivity analysis

1 INTRODUCTION

Today, in the area of structural modelling and due to the increasing costs of building materials, there is often a higher emphasis than before on structural optimisation both in terms of geometry and materials [1]. Unfortunately, the efficiency of mathematical optimisation algorithms decreases with the increasing number of design variables used [2]. One possible way to avoid this phenomenon is the performance of sensitivity analyses, which can dramatically decrease the number of design variables needed by identifying the variables which most affect the responses of the mathematical model.

In context of this article, explicit dynamics calculations require complex nonlinear material models for the description of real material behaviour. In the case of concrete material model 159 [3], [4], which is implemented in LS-DYNA [5], [6], there are more than 40 parameters. As a result, knowledge regarding the sensitivity of each parameter provides a large advantage.

The FE nonlinear explicit dynamic solver LS-DYNA was used for the numerical simulations. Sensitivity analysis was performed using optiSLang [7] software, which has implemented a large number of methods for sensitivity analysis and optimisation [8].

The objective of this article is to present a sensitivity analysis of the material model's parameters. The analysis was performed for a reinforced concrete beam which was subjected to impact loading by a steel hammer with a weight of 500 kg falling from a height of 20 cm.

2 METHODOLOGY

The methodology of the presented work is shown in Fig. 1. In the first phase, a geometrical model was created. Bodies were used for the concrete solid, supporting blocks and steel hammer, and lines for the reinforcing beams. The geometrical model was prepared for the mathematical model as a symmetrical half. In the second phase, discretisation was performed, material models were assigned to meshed parts, boundary and initial conditions were set, contacts were defined, and finally explicit analysis settings were defined. In the third phase, parameterization was conducted, and the sensitivity analysis was performed. Finally, the results were interpreted.

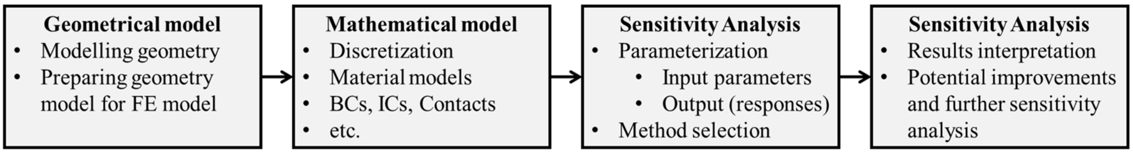

Fig. 1 Analysis workflow.

Geometrical and mathematical model

The geometrical model was created according to Fig. 2. In order to save computation time, only half of the beam was modelled, with symmetry being considered along the vertical longitudinal plane. The RC beam has a total length of 1.7 m and rests on two wooden blocks of 0.1 m in height, while the original cross section is 120 × 250 mm. The steel reinforcement consists of a lower bar of 14 mm radius, an upper bar of 10 mm radius and shear stirrups of 6 mm radius.

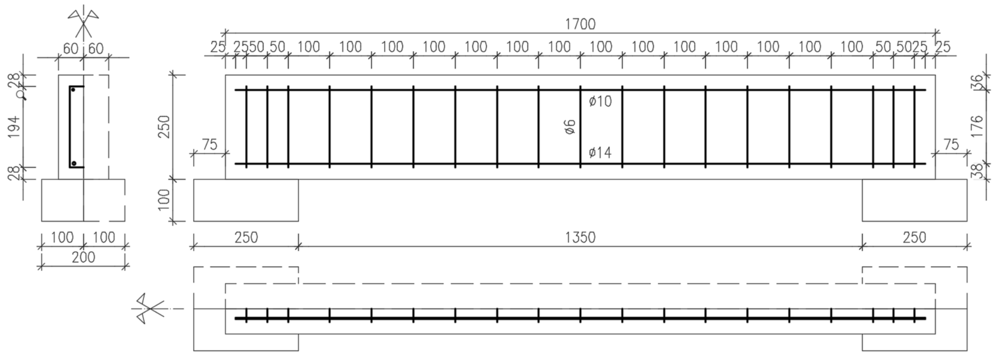

Fig. 2 Geometry and reinforcement of the RC beam and its supporting wooden blocks.

Discretisation of the geometry model was performed with an 8-node hexahedron element formulation (ELFORM = 2) for the solid elements and a Hughes-Liu element formulation (ELFORM=1) for the beam elements. The concrete and reinforcement were meshed with a 0.02 m element size, and the wooden blocks and steel hammer were meshed with a 0.03 m element size.

Material model 159 (*MAT_CSCM) was selected for the concrete solid elements. This complex Continuous Surface Cap Model was developed to predict the dynamic performance of concrete used in roadside safety structures, and it is suitable for a concrete structure subjected to impact loading [3]. This material model is defined by the yield function (1), which is based on three invariants and the cap hardening parameter κ as follows:

$$f(J_1, J'_2, J'_3, \kappa) = J'_2 - \Re^2 F_f^2 F_c \tag{1}$$

where F_f is the shear failure surface (2), F_c is the hardening cap (3), $\Re$ is the Rubin three-invariant reduction factor and J_i are the stress invariants. The Shear Failure Surface is defined as follows:

$$F_f(J_1) = \alpha - \lambda e^{-\beta J_1} + \theta J_1 \tag{2}$$

where α, β, λ and θ are material input parameters. The Cap Hardening Surface is defined as follows:

$$F_c(J_1, \kappa) = 1 - \frac{[J_1 - L(\kappa)][|J_1 - L(\kappa)| + J_1 - L(\kappa)]}{2[X(\kappa) - L(\kappa)]^2} \tag{3}$$

where $L(\kappa)$ is defined as follows:

$$L(\kappa) = \begin{cases} \kappa, & \text{if } \kappa > \kappa_0 \\ \kappa_0, & \text{otherwise} \end{cases} \tag{4}$$

where κ_0 is the value of J_1 at the initial intersection of the cap and shear surfaces before hardening is engaged. The intersection of the shear surface and the cap is at $J_1 = \kappa$. This intersection depends on the cap ellipticity ratio R, where R is the ratio of its major to minor axes as follows:

$$X(\kappa) = L(\kappa) + RF_f(I_1) \tag{5}$$

for which a detailed formulation can be found in [3].

Material model 24 (*MAT_PIECEWISE_LINEAR_PLASTICITY) was selected for the reinforcement beams. Material 24 is an elasto-plastic material with an arbitrary stress as a function of strain curve and arbitrary strain rate dependency, and also failure based on a plastic strain or a minimum time step size can be considered [6]. B500B steel was used for the reinforcement, which was defined in the mathematical model by a stress-strain diagram. The elastic material (*MAT_ELASTIC) was chosen for the solid elements of the wooden blocks and steel hammer. The wood had an elastic modulus of 300 MPa (radial/tangential direction) and a Poisson's ratio of 0.02, while the steel of the hammer had an elastic modulus of 210 GPa and a Poisson's ratio of 0.3. However, the mechanical properties of the steel and wood were not crucial because the sensitivity analysis was performed only for the mechanical properties of the concrete.

The boundary and initial conditions are shown in Fig. 3. The lower edges of the wooden blocks were constrained for displacement in all three directions. The symmetry plane was created by the LS-DYNA keyword card *BOUNDARY_SPC_SYMMETRY_PLANE_SET. The fall of the hammer was simulated by considering the initial velocity conditions to be -2 m/s, with all solids and beams loaded by gravity (9.81 m/s^2).

The contacts were created by the keyword *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_ID between the hammer and the concrete and between the wooden blocks and the concrete. Interaction between the concrete and the reinforcement was created by the keyword *CONSTRAINED_BEAM_IN_SOLID_ID. This keyword automatically invokes constraint-based coupling between the solid and beam nodes [5], [9].

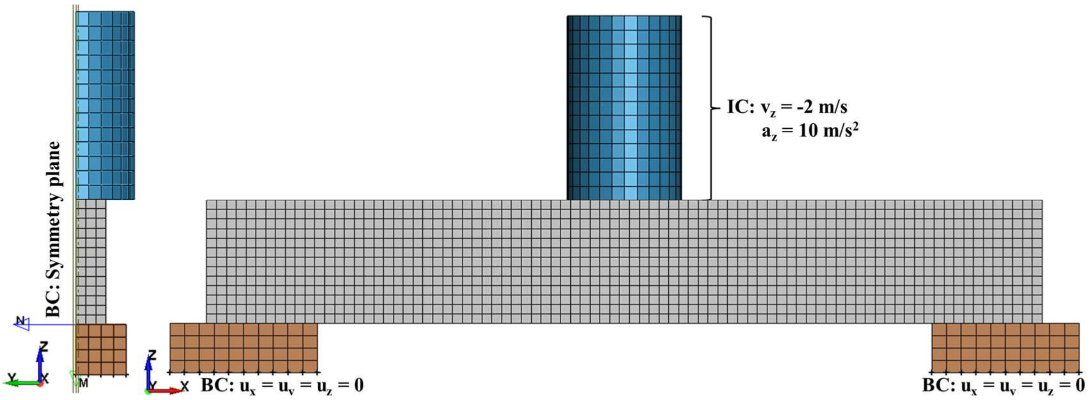

Fig. 3 Finite element mesh, boundary and initial conditions.

Parameterization and sensitivity analysis

The sensitivity analysis was performed using optiSLang software. The workflow of the analysis was created using the Sensitivity wizard. After running the Sensitivity wizard, Postprocessing and MOP were performed.

The first step was parameterization. Most of the input parameters of material model 159 were selected for parameterization. Reference values were created for the parameters by LS-DYNA for concrete with a compressive strength of 20 MPa and an aggregate size of 19 mm. The intervals or discrete values of the input parameters were then set.

In the second step, the responses of the model were selected. For the global model behaviour, the vertical displacement, velocity and acceleration of node 564 were set. For the concrete material behaviour, the stresses of three elements were selected: the longitudinal (tensile) stress of element 43, the longitudinal (compressive) stress of element 3103, and the shear stress of element 2073. The positions of the described nodes and elements are shown in Fig. 4, where the stresses, displacements and velocities of the reference model at time 0.00035 s are also shown.

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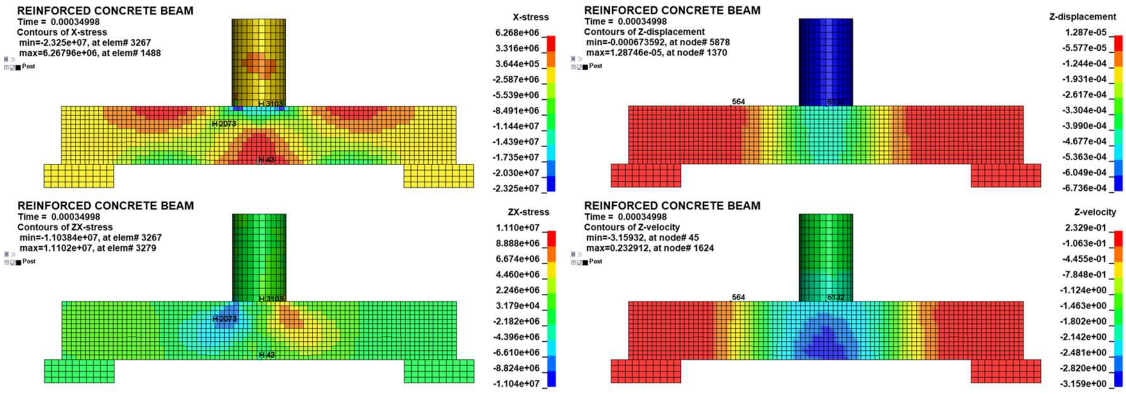

Fig. 4 Stresses, displacements and velocities for the reference model, and the positions of result nodes and elements.

The third step was performing the sensitivity analysis. Advanced Latin Hypercube Sampling was used to generate 500 designs (sets of parameters). The Polynomial, Moving Least Squares (MLS) and isotropic Kriging approximation methods were tested for the Metamodel of Optimal Prognosis (MOP).

3 RESULTS

The results of the sensitivity analysis can be interpreted using several methods. In this article, the MOP was used with the Coefficient of Prognosis (*CoP*) to interpret the sensitivity between the input parameters and the output/result responses. The *CoP* is an independent measure of model quality, which is defined as follows:

$$CoP = 1 - \frac{SS_E^{Prediction}}{SS_T} \tag{6}$$

where $SS_E^{Prediction}$ is the sum of the squared prediction errors and SS_T is equivalent to the total variation. A further description can be found in [2] and [8].

In Fig. 5 the *CoP* is shown for stresses in concrete elements for the pre-peak, peak and post-peak values of these stresses. As the responses are time-dependent, a coarse time stepping for result responses was utilised and then can be considered: for element 43 the peak was at time step 2, for element 3103 it was at time step 5, and for element 2073 it was at time step 4; see the stress-time step diagrams in Fig. 6.

For the element stresses shown in Fig. 5, the *CoP* ranges in value from 62% to 100%. The result can be considered a good approximation if the full model *CoP* (of the response) is greater than 90%. Therefore, any response parameter that has lower values should be considered carefully or should be refined, for example by another set of parameters, which can be performed conveniently in optiSLang with the Adaptive Metamodel of Optimal Prognosis (AMOP).

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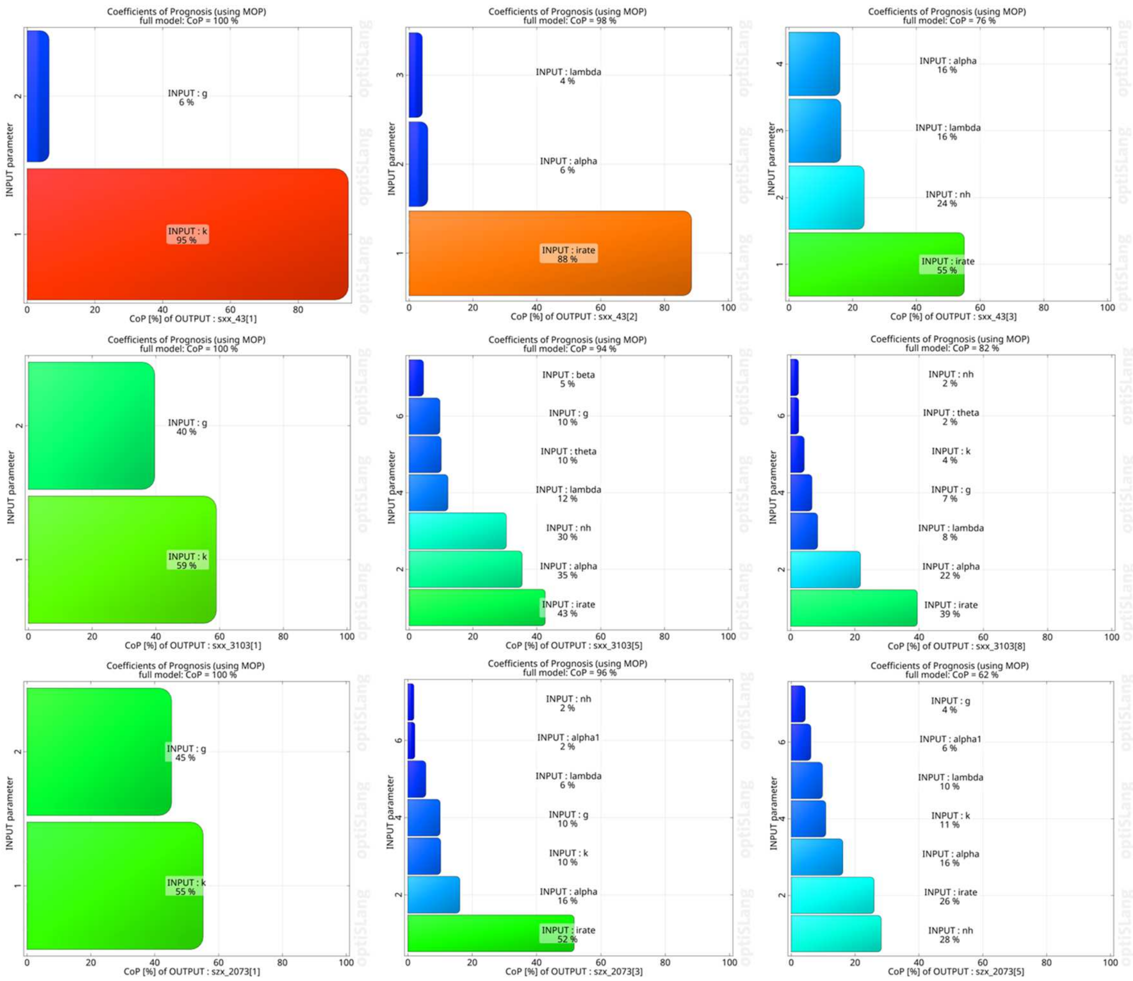

Fig. 5 Coefficient of Prognosis of element stresses and the most influential input parameters.

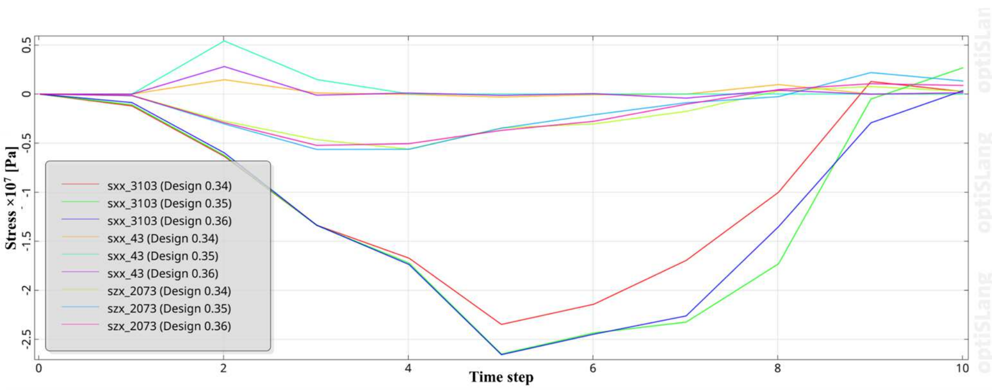

Fig. 6 Stress-time step diagrams of designs 34, 35 and 36.

Fig. 7 shows the Coefficients of Prognosis of node 564. All models obtained $CoP \geq 90\%$, so the responses can be considered good approximations.

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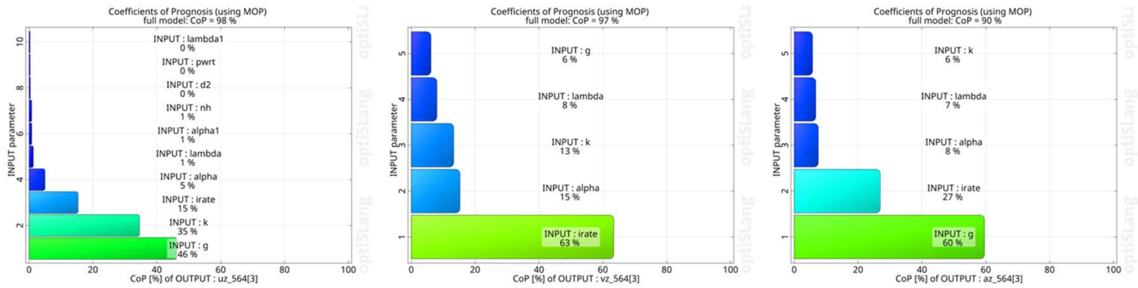

Fig. 7 Coefficient of Prognosis of node displacement, velocity and acceleration.

4 DISCUSSION

The results above show that the pre-peak stresses in concrete elements are dominantly sensitive to parameters *K* and *G* (shear and bulk modulus), but this could be affected by the fact that the dynamic load imposed by the steel hammer has not influenced the beam yet, and beam is loaded just by self-weight.

In the case of the peak stress, the most sensitive parameter is *irate*, which turns the rate effect of the material model on and off. The next most sensitive parameters are *alpha*, *nh* and *lambda*.

The post-peak stress sensitive parameters should be considered carefully because the response CoPs are smaller than 90%. These responses should be accurate after being refined using the AMOP.

Due to the robustness of the sensitivity analysis (up to 40 input parameters) and the time-dependent analysis, only stresses and deformations were adopted as response parameters. The next step of this research will be to improve the sensitivity analysis by including responses for plasticity and crack width in concrete, and stresses and plasticity in reinforcement. After improving the sensitivity analysis, the next step will be the optimisation of input parameters and the inverse analysis of reinforced concrete structures.

5 CONCLUSION

The main goal of this article was to perform the sensitivity analysis of a reinforced concrete beam subjected to impact loading by a steel hammer falling from a height of 20 cm. The sensitivity analysis was performed for most of the input material parameters of material model 159, which is implemented in LS-DYNA. Stresses (tension, compression and shear) in the concrete elements and the displacement, velocity and acceleration of the node on the upper surface of the beam were selected as response parameters. Response values at various time steps were also taken into account.

The presented results meet the preliminary expectations, but there are still some points to improve:

- AMOP should be used to achieve higher *CoP* values,
- More responses (plasticity, crack width, fracture and damage energy, and responses of reinforcement, etc.) could be included,

Despite the above-mentioned factors, the presented results can be considered useful in the context of understanding structures and material behaviour under impact loading using a complex material model. The next steps of this research will involve the improvement of the analysis results by incorporating the above factors, and then the performance of optimisation and inverse analysis.

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