

PAPER • OPEN ACCESS

Steel Fibre Reinforced Concrete Simulation with the SPH Method

To cite this article: Martin Hušek *et al* 2017 *IOP Conf. Ser.: Mater. Sci. Eng.* **245** 032070

View the [article online](#) for updates and enhancements.

Related content

- [Comparison of meshfree and mesh-based methods for boundary value problems in physics](#)
P Niraula, Y Han and J Wang
- [Effect of Thickness and Fibre Volume Fraction on Impact Resistance of Steel Fibre Reinforced Concrete \(SFRC\)](#)
Zakaria Che Muda, Fathoni Usman, Agusril Syamsir *et al.*
- [Punching Shear in Steel Fibre Reinforced Concrete Slabs Without Traditional Reinforcement](#)
K H Tan and A Venkateshwaran



IOP | ebooks™

Bringing you innovative digital publishing with leading voices to create your essential collection of books in STEM research.

Start exploring the collection - download the first chapter of every title for free.

Steel Fibre Reinforced Concrete Simulation with the SPH Method

Martin Hušek¹, Jiří Kala¹, Petr Král¹, Filip Hokeš¹

¹ Faculty of Civil Engineering, Institute of Structural Mechanics, Brno University of Technology, Veveří 331/95, 602 00 Brno, Czech Republic

husek.m@fce.vutbr.cz

Abstract. Steel fibre reinforced concrete (SFRC) is very popular in many branches of civil engineering. Thanks to its increased ductility, it is able to resist various types of loading. When designing a structure, the mechanical behaviour of SFRC can be described by currently available material models (with equivalent material for example) and therefore no problems arise with numerical simulations. But in many scenarios, e.g. high speed loading, it would be a mistake to use such an equivalent material. Physical modelling of the steel fibres used in concrete is usually problematic, though. It is necessary to consider the fact that mesh-based methods are very unsuitable for high-speed simulations with regard to the issues that occur due to the effect of excessive mesh deformation. So-called meshfree methods are much more suitable for this purpose. The Smoothed Particle Hydrodynamics (SPH) method is currently the best choice, thanks to its advantages. However, a numerical defect known as tensile instability may appear when the SPH method is used. It causes the development of numerical (false) cracks, making simulations of ductile types of failure significantly more difficult to perform. The contribution therefore deals with the description of a procedure for avoiding this defect and successfully simulating the behaviour of SFRC with the SPH method. The essence of the problem lies in the choice of coordinates and the description of the integration domain derived from them – spatial (Eulerian kernel) or material coordinates (Lagrangian kernel). The contribution describes the behaviour of both formulations. Conclusions are drawn from the fundamental tasks, and the contribution additionally demonstrates the functionality of SFRC simulations. The random generation of steel fibres and their inclusion in simulations are also discussed. The functionality of the method is supported by the results of pressure test simulations which compare various levels of fibre reinforcement of SFRC specimens.

1. Introduction

New modifications of both standard and reinforced varieties of concrete are created almost every day. This is perfectly normal; research keeps forging ahead. Unfortunately, it is very hard to discover how to work with these new materials when designing structures. This is true of the specific material discussed in this contribution, steel fibre reinforced concrete (SFRC). This is, technically speaking, concrete strengthened by scattered steel reinforcement in the form of short steel fibres.

Even though SFRC can be considered a very well thought-out concept in that the material has increased ductility and a lower tendency towards microcrack formation, its negative aspects must also not be forgotten. In this case, the difficulty of its numerical simulation during the design stages of



realizing a structure can be considered a disadvantage. The said difficulty is due to the lack of knowledge about the heterogeneous structure of the material to be simulated.

The first problem is the sheer complexity of concrete structure. Its material parameters are very hard to determine [1, 2]. Moreover, when determining these parameters, it is not known in advance which are necessary and which are not [3, 4]. Another problem is with the correct depiction of the freely dispersed fibre reinforcement. Unfortunately, the technical processes available are not sufficiently advanced to be able to guarantee the position of the reinforcement with high precision. This means that SFRC can only be simulated to a certain degree of probability in this way. As in many other cases, we are therefore forced to include various sensitivity analyses in the design stages, which can be time-consuming [5-7]. Even if it were possible to replace the SFRC structure in a simple and yet accurate way – for example by creating an equivalent material, new problems could arise. Complex loading procedures [8-11] often cause materials to exhibit complex responses. Moreover, standard mesh-based numerical methods, for example the Finite Element Method (FEM), cannot be used in cases of high-speed loading [12-14]. However, high-speed loading can be simulated using the Smoothed Particle Hydrodynamics (SPH) method. With regard to the desired success of the simulation, an equivalent material must not be used. The main reason is that concrete and steel behave differently as loading speed increases during their mutual interaction. From this aspect, it would be a mistake to replace the complex structure of SFRC with an equivalent material. The SPH method suffers from “tensile instabilities”, though, which can be reformulated in the case of SFRC as the inability to simulate a ductile type of failure (particularly in the case of steel reinforcement) [15].

The contribution describes one of the possible procedures that can be used to simulate SFRC successfully using the SPH method. The whole procedure and its use are presented in connection with a compression test performed on cylindrical SFRC specimens. Various levels of reinforcement of the SFRC variants are compared. The results show the success of the described procedure.

2. Background of the SPH formulation

The formulation of the SPH method is often divided into two key steps. The first step is the integral representation of field functions, and the second one is particle approximation. Assuming that the finite volume ΔV_j is assigned to the SPH particle j , the following relationship applies

$$m_j = \Delta V_j \rho_j \quad (1)$$

where m_j and ρ_j are the mass and density of the particle j . The value of the monitored quantity $f(\mathbf{x}_i)$, which is the product of integral representation and particle approximation operations, can thus be written as

$$f(\mathbf{x}_i) \approx \sum_{j=1}^N \frac{m_j}{\rho_j} f(\mathbf{x}_j) W(\mathbf{x}_i - \mathbf{x}_j, h) \quad (2)$$

where W is the so-called smoothing function and h denotes the smoothing length defining the influence area of the smoothing function W . Equation (2) states that the value of a function at particle i is approximated using the average of those values of the function at all the particles in the support domain of the particle i weighted by the smoothing function shown in figure 1, [15].

3. Problem with the support domain

The extent of the support domain is defined according to figure 1 as the size of the generally variable parameter h , which is called the smoothing length. Parameter h can also be multiplied by constant κ . Particles which are inside the support domain attributable to particle i are called neighbouring particles.

If the resultant value of the product κh in each time step of the numerical simulation is the same, there can be the decrease in the number of neighbouring particles and thus also the decrease in the accuracy of the solution due the effect of excessive deformations (i.e. during the mutual divergence of the SPH particles). It is advisable to change the size of the support domain during the calculation in such a way that the number of neighbouring particles is constant.

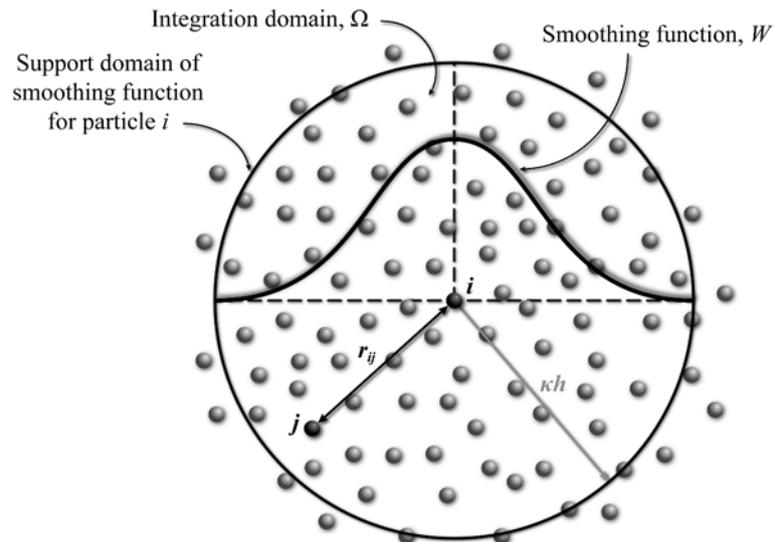


Figure 1. The particle approximations using particles within the support domain of the smoothing function W for particle i

There are many ways to dynamically develop h so that the number of neighbouring particles remains relatively constant. In 1989, Benz [16] suggested a method of developing the smoothing length. This method uses the time derivative of the smoothing function in terms of the continuity equation

$$\frac{dh}{dt} = -\frac{1}{d} \frac{h}{\rho} \frac{d\rho}{dt} = \frac{1}{d} h \nabla \cdot \mathbf{v} \quad (3)$$

where d is the number of dimensions and $\nabla \cdot \mathbf{v}$ is the divergence of the flow. This means that the smoothing length increases when particles separate from each other and reduces when the concentration of particles is significant. It varies in order to keep the same number of particles in the neighbourhood. Equation (3) can be discretized using SPH approximations and calculated with other differential equations in parallel [15].

4. Eulerian and Lagrangian kernels

The approach in (3) is applicable when the integral representation of field functions is formulated in spatial coordinates (Eulerian kernel). With a Eulerian kernel, the smoothing length of a particle changes through the calculation. As a consequence, the neighbourhood of each particle needs to be updated at each time step [17]. However, nothing exists to prevent the number of neighbouring particles changing. Despite the implementation of (3), the particles can enter and leave the support domain and thus tensile instability can occur. In other words, this means that the possibility of simulating ductile failure during the excessive divergence of particles from one another disappears. The behaviour of a Eulerian kernel during a calculation can be seen in figure 2.

However, when the integral representation of field functions is formulated in the material coordinates (Lagrangian kernel), the neighbours' list of each SPH particle is defined in the initial configuration and remains constant throughout the whole calculation. It means that the support domain of a particle follows

material deformation in order to always keep the same neighbours. It provides a way of solving tensile instabilities. The behaviour of a Lagrangian kernel during a calculation can be seen in figure 3. To eliminate the tensile instabilities in the simulations the Lagrangian kernel was selected.

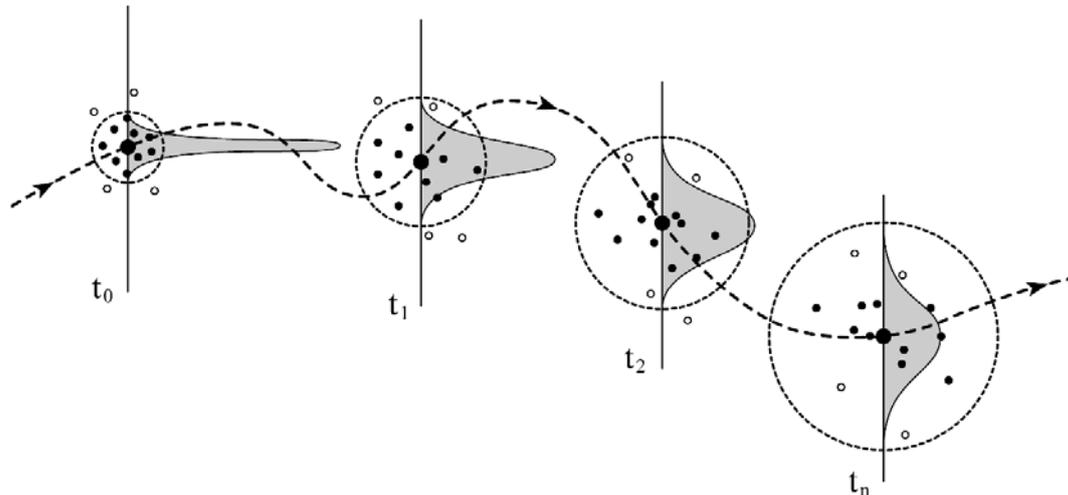


Figure 2. Eulerian kernel – the amount of particles within the support domain might not be constant

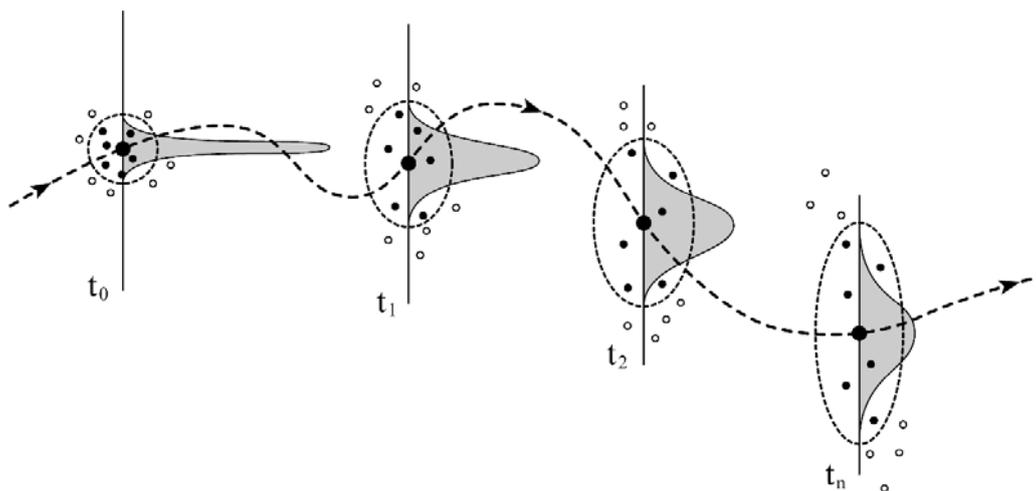


Figure 3. Lagrangian kernel – the amount of particles within the support domain is constant

5. The fibre distribution and experiment set up

For the evaluation of the functionality of a Lagrangian kernel and generally of the ability of the SPH method to accurately depict the behaviour of SFRC, static pressure tests performed on cylindrical SFRC specimens with a height of 300 mm and a diameter of 150 mm were simulated. Loading took place in the form of controlled displacement while the stress–strain curve was recorded. To enable a comparison of the response, various levels of reinforcement (volume percentages) were used – 0%, 0.5%, 1.0% and 2.0%, as can be seen in figure 4.

The discretization of the cylindrical specimen was carried out using SPH particles with a regular grid distribution. The specimen contained a total of 24,050 SPH particles. The Continuous Surface Cap Model (CSCM) [18, 19] was used as the concrete material model. The material parameters are shown in table 1. Fibre reinforcement was then generated for the given volume. The reinforcement was of the “hooked end” type, with a length of 50 mm and a diameter of 1.05 mm. The material model of the reinforcement used was a simple plastic model with kinematic hardening. The material parameters are shown in table 2. The reinforcement was generated using a random distribution algorithm in such a way

that it fills the volume of the cylinder as regularly as possible. The random distribution generator is described in more detail in [20]. The individual fibres of the reinforcement were discretized as 1D line bodies. This means that the SPH particles were all in one row. In this way, the possibility of depicting the bending stiffness disappears though with regard to the profile of the fibres, this is not needed. The fibres are used mainly for tensile stress, not bending. The simulations were performed via the LS-DYNA program [21].

Table 1. The material parameters for CSCM concrete model

Mass density, ρ_c (kgm^{-3})	2207
Compressive strength, f_c (MPa)	47
Initial shear modulus, G (GPa)	12.92
Initial bulk modulus, K (GPa)	14.15
Poisson's ratio, ν_c	0.18
Fracture energy, G_F (Jm^{-2})	83.25
Maximum aggregate size, a_g (mm)	8

Table 2. The material parameters for plastic kinematic steel model

Mass density, ρ_s (kgm^{-3})	7850
Yield strength, f_y (MPa)	950
Ultimate tensile strength, f_u (MPa)	1000
Young's modulus, E (GPa)	210
Tangent modulus, E_t (GPa)	105
Poisson's ratio, ν_s	0.27

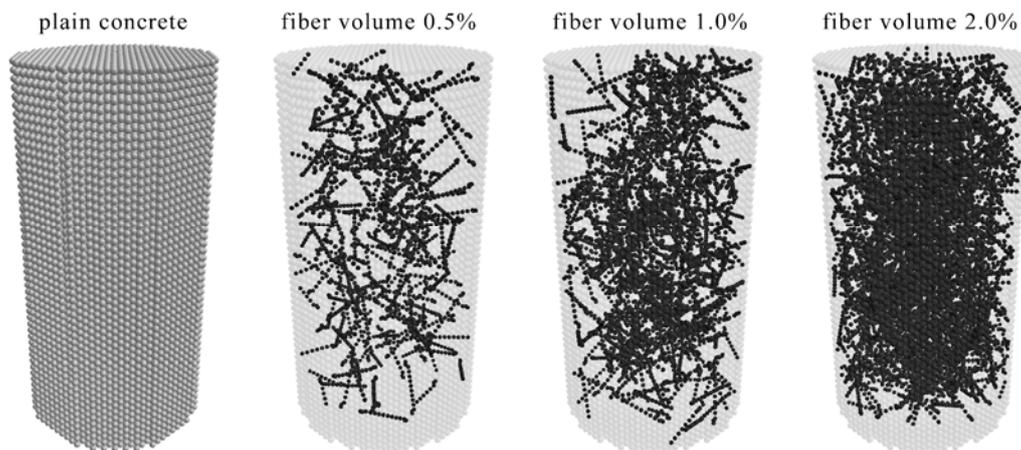


Figure 4. Fibre distribution of the tested specimens

6. Results and discussions

This section discusses the Lagrangian kernel functionality and also compares the behaviour of the generated models with a different reinforcement percentage. The gray-marked portions of the images invariably represent a crackless material, whereas the red sectors stand for complete failures (mostly main cracks). All the results were captured at the same moment.

In the case of a variant of the tested specimen with 0% reinforcement (plain concrete), one of the basic types of failure were expected – the creation of a main slanting crack or several vertical cracks. It

is clear from figure 5 that a main slanting crack was created. Its stress–strain curve is shown in figure 6. The failure of the variant with 0.5% reinforcement was localized again in one main crack. However, several findings have been obtained from the stress–strain curve. The initial stiffness and compressive strength increased while the descending branch of the diagram shifted slightly towards the ductile field of failure. In the case of 1.0% and 2.0% reinforcement, the mentioned changes are further amplified. The failure thus transforms from one main crack into a large plastic area. The results are consistent with experiments, see [22]. The functionality of the described method of SFRC simulation is clear from the comparison in figure 5 and the stress–strain curves in figure 6, as are its positive aspects as a construction material.

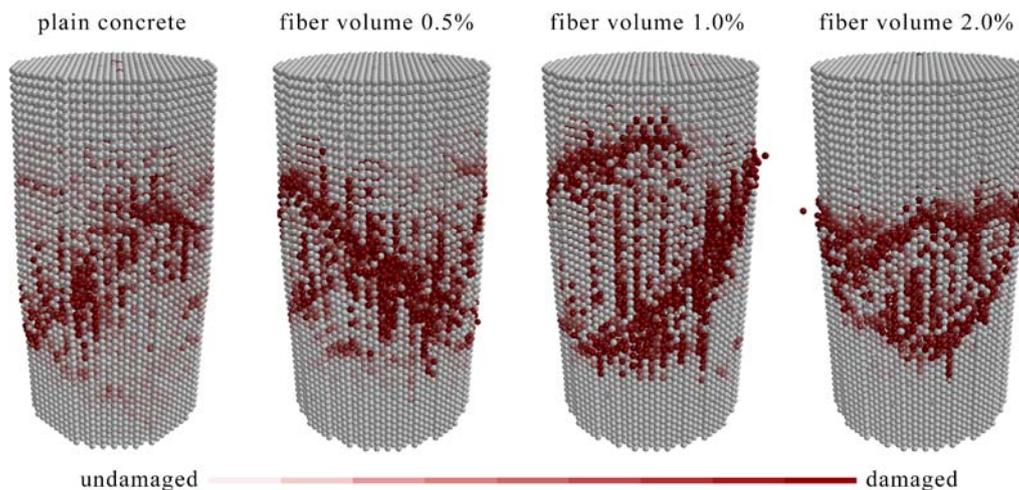


Figure 5. Deformation of the tested specimens

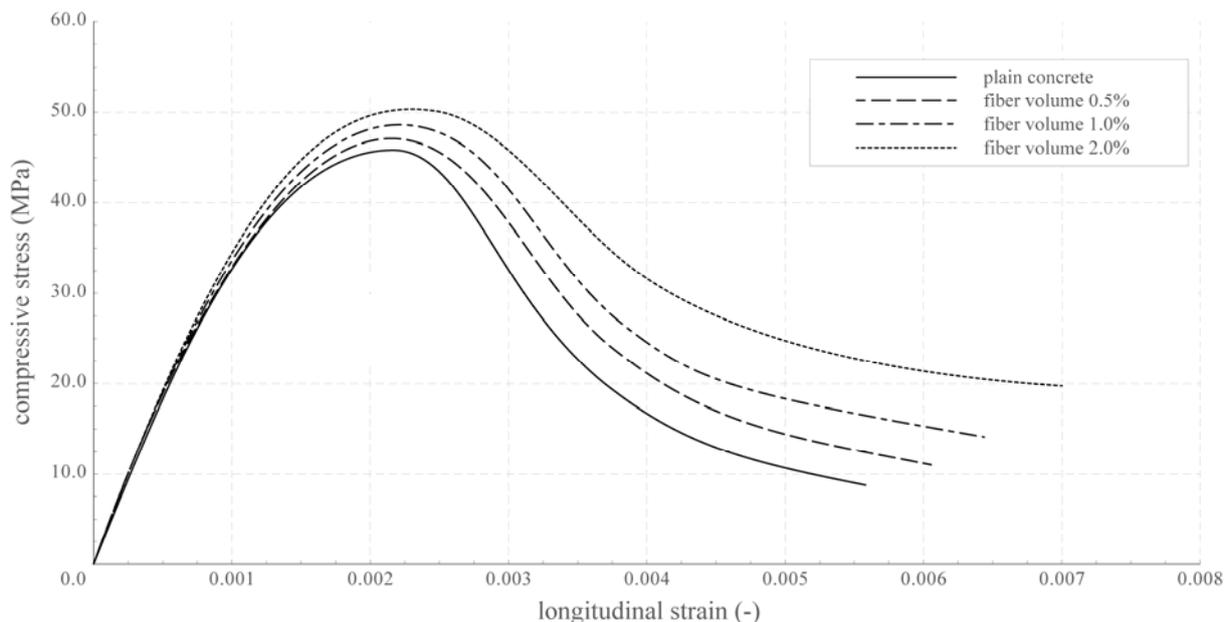


Figure 6. Stress–strain curves of the tested specimens

7. Conclusions

The contribution describes one of the possible procedures for the simulation of steel fibre reinforced concrete (SFRC) using the Smoothed Particle Hydrodynamics (SPH) method. In its basic formulation,

the SPH method is able to simulate the failure of quasi-brittle materials. The basic formulation of the SPH method is defined in the spatial coordinates (Eulerian kernel). Unfortunately, with regard to the presence of the numerical defect referred to as tensile instability, it is not suitable for simulations of ductile types of failure. As SFRC is a combination of a quasi-brittle material (concrete) and a ductile material (steel), the SPH method needs to be formulated in the material coordinates (Lagrangian kernel). In the case of the Lagrangian kernel the neighbours' list of each SPH particle is defined in the initial configuration and remains constant throughout the whole calculation. Thanks to this, ductile types of failure can also be simulated, or a combination of ductile and quasi-brittle failure as in the case of SFRC.

Proof of the functionality of the described procedure is presented with regard to a static compression test performed on SFRC cylindrical specimens. The behaviour of various levels of reinforcement is compared. The results show the functionality of the described procedure and simultaneously the good mechanical properties of SFRC.

Acknowledgments

This outcome has been achieved with the financial support of the project GACR 17-23578S "Damage assessment identification for reinforced concrete subjected to extreme loading" provided by the Czech Science Foundation, and also with the support of the project FAST-S-16-3718 "Advanced numerical methods with complex material models" provided by the Brno University of Technology fund for specific university research.

References

- [1] P. Kral, P. Hradil, and J. Kala, "Inverse Identification of the Material Parameters of a Nonlinear Concrete Constitutive Model Based on the Triaxial Compression Strength Testing," *Frattura ed Integrità Strutturale (Fracture and Structural Integrity)*, vol. 11, pp. 38–46, 2017.
- [2] P. Kral, J. Kala, and P. Hradil, "Verification of the elasto-plastic behavior of nonlinear concrete material models," *International Journal of Mechanics*, vol. 10, pp. 175–181, 2016.
- [3] F. Hokes, and J. Kala, "Selecting the objective function during the inverse identification of the parameters of a material model of concrete," *Frattura ed Integrità Strutturale (Fracture and Structural Integrity)*, vol. 11, pp. 7–16, 2017.
- [4] F. Hokes, J. Kala, and O. Krnavek, "Nonlinear numerical simulation of a fracture test with use of optimization for identification of material parameters," *International Journal of Mechanics*, vol. 10, pp. 159–166, 2016.
- [5] Z. Kala, "Sensitivity and reliability analyses of lateral-torsional buckling resistance of steel beams," *Archives of Civil and Mechanical Engineering*, vol. 15, no. 4, pp. 1098–1107, 2015.
- [6] Z. Kala, "Global Sensitivity Analysis in Stability Problems of Steel Frame Structures," *Journal of Civil Engineering and Management*, vol. 22, no. 3, pp. 417–424, 2016.
- [7] Z. Kala, and J. Vales "Global Sensitivity Analysis of Lateral-torsional Buckling Resistance Based on Finite Element Simulations," *Engineering Structures*, vol. 134, pp. 37–47, 2017.
- [8] J. Kralik, "Safety of nuclear power plants under the aircraft attack," *Applied Mechanics and Materials*, vol. 617, pp. 76–80, 2014.
- [9] J. Kralik, and M. Baran, "Numerical analysis of the exterior explosion effects on the buildings with barriers," *Applied Mechanics and Materials*, vol. 390, pp. 230–234, 2013.
- [10] J. Kralik, "Optimal design of NPP containment protection against fuel container drop," *Advanced Materials Research*, vol. 688, pp. 213–221, 2013.
- [11] J. Kala, P. Hradil, and M. Bajer, "Reinforced concrete wall under shear load – experimental and nonlinear simulation," *International Journal of Mechanics*, vol. 9, pp. 206–212, 2015.
- [12] J. Kala, and M. Husek, "Useful material models of concrete when high speed penetrating fragments are involved," *Proceedings of the 9th International Conference on Continuum Mechanics*, vol. 15, pp. 182–185, 2015.

- [13] J. Kala, and M. Husek, “High speed loading of concrete constructions with transformation of eroded mass into the SPH,” *International Journal of Mechanics*, vol. 10, pp. 145–150, 2016.
- [14] J. Kala, and M. Husek, “Improved element erosion function for concrete-like materials with the SPH method,” *Shock and Vibration*, vol. 2016, pp. 1–13, 2016.
- [15] G. R. Liu, and M. B. Liu, “*Smoothed particle hydrodynamics: a meshfree particle method*,” World Scientific Publishing Co. Pte. Ltd, 2003.
- [16] W. Benz, “Smoothed particle hydrodynamics: a review,” *NATO Workshop*, Les, Arcs, France, 1989.
- [17] M. Husek, J. Kala, P. Kral, and F. Hokes, “Effect of the support domain size in SPH fracture simulations,” *International Journal of Mechanics*, vol. 10, pp. 396–402, 2016.
- [18] Y. D. Murray, “User’s manual for LS-DYNA concrete material model 159,” FHWA-HRT-05-062, 2007.
- [19] Y. D. Murray, A. Abu-Odeh, and R. Bligh, “Evaluation of concrete material model 159,” FHWA-HRT-05-063, 2006.
- [20] M. Husek, F. Hokes, J. Kala, and P. Kral, “Inclusion of randomness into SPH simulations,” *WSEAS Transactions on Heat and Mass Transfer*, vol. 12, pp. 1–10, 2017.
- [21] Livermore Software Technology Corporation (LSTC), “*LS-DYNA theory manual*,” LSTC, Livermore, California, USA, 2016.
- [22] C.D. Johnston, “Steel fiber reinforced mortar and concrete: a review of mechanical properties,” *ACI Special Publication*, sp. 44, pp. 127–142, 1974.