Available online at www.sciencedirect.com

ScienceDirect

Procedia Structural Integrity 9 (2018) 272–278

Structural Integrity
Procedia

www.elsevier.com/locate/procedia

IGF Workshop "Fracture and Structural Integrity"

Analysis of reinforced concrete slabs under blast loading

Gianluca Iannitti[a], Nicola Bonora[a], Giuseppe Curiale[b], Stefano De Muro[b], Sonia Marfia[a], Andrew Ruggiero[a], Elio Sacco[c], Sara Scafati[b], Gabriel Testa[a]

[a]*Department of Civil and Mechanical Engineering, University of Cassino and Southern Lazio, via G. di Biasio 43, 03043, Cassino, Italy*
[b]*Protezione Aziendale, Area Tecnica – Rete Ferroviaria Italiana S.p.A., Piazza della Croce Rossa 1, 00161 Italy*
[c]*Department of Structures in Engineering and Architecture, University of Naples Federico II, Via Claudio 21, 80125, Naples, Italy*

Abstract

Aim of the present paper is the study of the blast effects on reinforced concrete slabs used for civil buildings. Reinforced concrete slab samples with and without partitions subjected to explosions are numerically analyzed adopting the explicit finite element code LS-DYNA. In particular, the explosive is considered in direct contact with the sample surface. Each material composing the slab is modeled adopting a suitable non linear constitutive model. The partitions are modelled as rigid bodies and they are placed in two different positions. Numerical analyses are performed on the slabs with and without partitions, considering the same amount of explosive, in order to determine the influence of partitions on the blast resistance of the slabs. Comparisons in terms of the damage produced in the slab are carried out.

Peer-review under responsibility of the Gruppo Italiano Frattura (IGF) ExCo.

Keywords: Blast effects; Concrete slabs; Direct contact explosion; Partitions.

---

1. Introduction

Recent terrorist attacks have pointed out that the public buildings are not safe places in case of explosion. Although the main cause of injuries against people are due to pressures and heat of the explosion, there are other threats that can be hazardous at the same manner. After an explosion, falling debris, breaking windows and, eventually, a partial or complete building collapse are further causes of injuries. With this in mind, to improve the blast resistance of buildings means to save lives. This can be achieved designing the right countermeasures expressly developed to mitigate the effects of blast loads on the buildings in order to reduce the collateral effects of the explosion. Unfortunately, there are no standards that can give the guideline to improve the blast resistance of buildings, but this can be done through experimental and numerical analysis.

2452-3216
Peer-review under responsibility of the Gruppo Italiano Frattura (IGF) ExCo.
10.1016/j.prostr.2018.06.035

Moreover, while there are experimental and theoretical-numerical investigations concerning structures hit by external explosions (Fachinger et al., 2004, Fachinger, 2006, Wu et al., 2007, Yi et al., 2012, Foglar and Kovar, 2013, Li et al., 2015), much less studies have been developed related to in-door explosion, typical of terroristic attacks (Wang et al., 2013, Shi et al., 2015, Ruggiero et al., 2018, Marfia et al., 2018).

This work is part of a research activity aimed to analyze the blast resistance of a standard reinforced concrete floor slab used for civil buildings and to individuate potential reinforcing actions. The following configurations were experimentally and numerically investigated: 1) plain slabs loaded with three different masses (2.1, 6.3, and 10.5 kg) of EXEM 100 in direct contact with the floor (Ruggiero et al. (2018)); 2) slabs positioned in a more realistic two floor frame, loaded with two different charges (10.5 and 16.8 kg of EXEM 100), in three different configurations, plain, slabs reinforced with a Kevlar layer, and slabs reinforced with honeycomb panel (Marfia et al. (2018)).

In the present work, taking the plain slabs loaded with 6.3 kg of explosive as a reference condition, the effect produced by the presence of partitions is numerically analyzed. The study aims to investigate the influence of elements likely present in civil buildings on the blast action.

Numerical simulations have been carried out with the explicit finite element code LS-DYNA. All the materials composing the slab are modeled adopting a suitable non linear constitutive model. The partitions are modeled as rigid bodies. Numerical results put in evidence the effect of partitions on the mechanisms of damage development into the slabs.

2. Reinforced concrete slab

The study is focused on reinforced concrete slabs, typical of civil constructions, with dimensions 3600 mm x 4000 mm x 340 mm. They are made by three predalles, each one with dimensions 1200 mm x 4000 mm with a pre-cast concrete plank characterized by 50 mm of thickness and reinforced with a square net of ϕ6 mm steel bars with dimensions 150 mm x 150 mm. Each predalles contains two polystyrene blocks and three trusses. Each truss with ϕ8 mm and ϕ12 mm bars is placed in the longitudinal direction between two adjacent polystyrene blocks.

In situ concrete is poured over the predalles to fill the gaps creating a rib between two adjacent polystyrene blocks and a topping with 50 mm thickness. The topping is reinforced by a square steel net of ϕ6 mm bars with dimensions 150 mm x 150 mm. The slab is completed with a waterproofing sheet and a screed of 100 mm of thickness, made in fiber reinforced concrete. A square steel mesh of ϕ6 mm wires with dimensions 150 mm x 150 mm is introduced inside the fiber reinforced concrete screed. The scheme of the slab is represented in Fig. 1. Furthermore, the fiber reinforced concrete is obtained by adding to the concrete matrix synthetic fibers with high mechanical strength with a density of 8 kg/m^3.

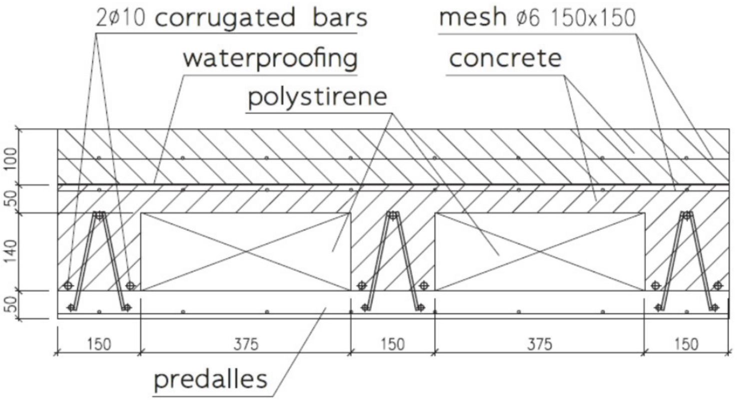

Fig. 1. Analysed slab.

3. Numerical modeling

The explicit finite element code LS-DYNA is adopted to perform numerical analyses of the slab, described in the previous section, with and without partitions. Because of the double symmetry of the problem, only a quarter of the structure is modelled, as represented in Fig. 3, prescribing suitably boundary conditions at the analysed quarter edges placed on the symmetric axes.

Three types of Lagrangian elements are used:

- bricks for concrete;
- shells for the waterproof sheet
- beams for the reinforcing steel.

The slab edge orthogonal to the direction of the ribs and of the predalles is simply supported.

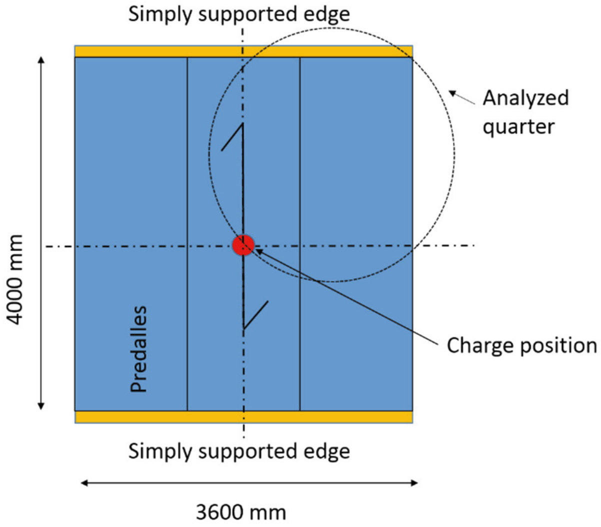

Fig. 2. Scheme of the Slab.

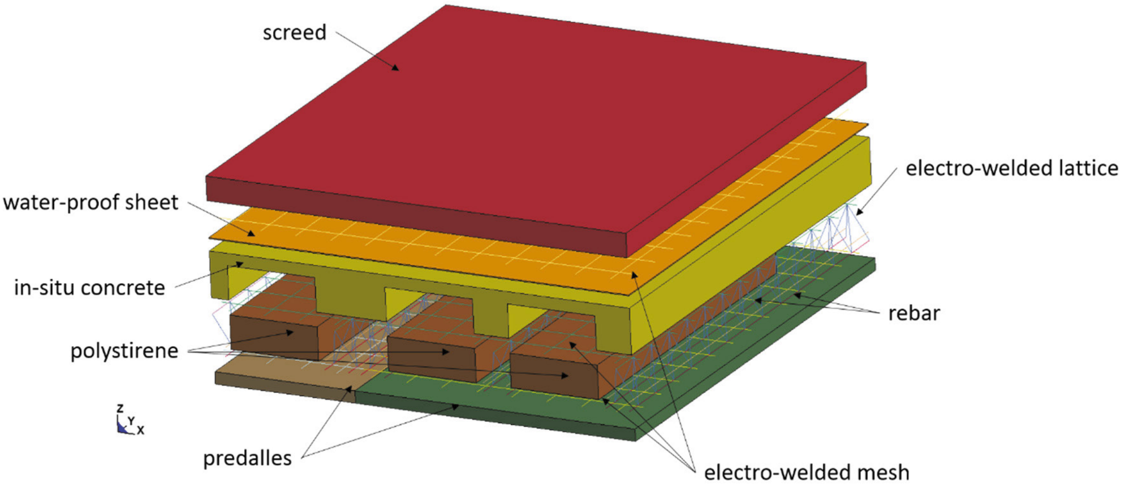

Fig. 3. Numerical scheme.

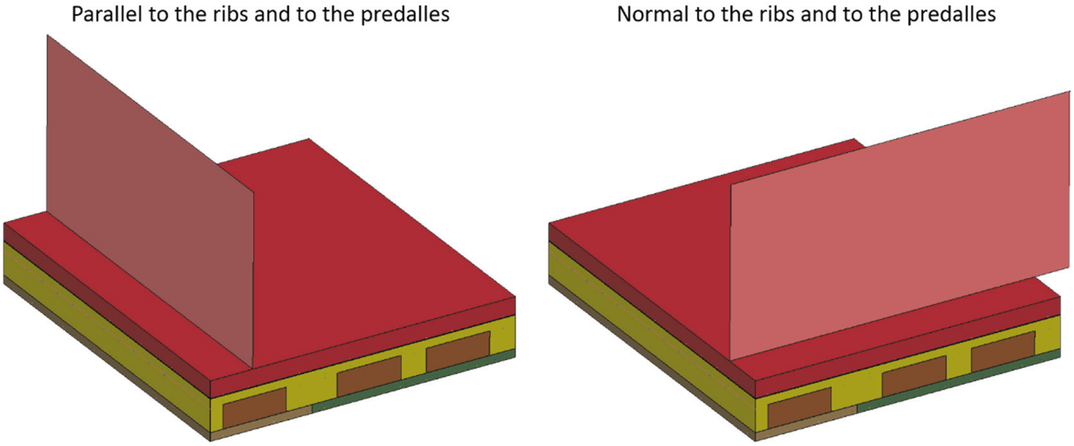

Fig. 4. Scheme of the partitions.

Three different configurations are analysed: the first one without partitions, in the other two partitions are taken into account.

In particular, the partitions are modelled as rectangular rigid bodies, with length equal to 2000 mm and height equal to 1000 mm. The partition is placed at 250 mm from the symmetry plane. In the second analyzed slab the partition is placed parallel to the direction of the ribs and the predalles, while in the third analyzed slab it is normal to that direction, as represented in Fig. 4.

An explosive charge equal to 6.3 kg of EXEM 100, placed at the centre of the slab and in contact with the upper surface, is considered. The blast wave development and propagation are modeled with an arbitrary Lagrangian-Eulerian (ALE) technique. The fluid-structure interaction (FSI) is applied adopting the penalty coupling method. Details on the blast wave modelling (i.e. physical properties, models and relative coefficients adopted for explosive and air) can be found in (Ruggiero et. al (2018)).

1.1. Constitutive models for solid elements

In this section, the constitutive models adopted for the different materials constituting the slabs are briefly described.

Concrete

In order to describe the mechanical response of concrete, the model proposed by the Riedel-Hiermaier-Thoma (RHT) is considered. It is the damage-viscoplasticity model proposed by Riedel et al. (1999), Riedel (2000). The model takes into account the porous compaction of concrete and it is characterized by a strength model made by three limit surfaces accounting for pressure, stress triaxiality and strain rate.

A detailed description of the quite complex model can be found in Riedel et al. (1999), Riedel (2000). It requires in input 38 coefficients that are reported in Ruggiero et al. (2018).

The same model is adopted to model also the fiber reinforced concrete, setting properly the model parameters.

Steel

The Johnson and Cook model 0 is adopted to describe the mechanical behavior of steel that constitutes the reinforcing elements. The model accounts for the strain hardening and the strain rate effect. The Johnson and Cook model implemented for beam element in LS-DYNA does not account for temperature effect nor for damage. Thus, an erosion criterion is considered for which the maximum allowable stress is set equal to 500 MPa. The adopted model coefficients are reported in Ruggiero et al. (2018).

Waterproof sheets

The waterproof sheet was model with the Mooney-Rivlin model (Mooney, 1940; Rivlin, 1948). The model is hyperelastic and the material parameters are reported in Ruggiero et al. (2018).

Expanded polystyrene

The MAT_CRUSHBLE_FOAM material model available in LS-DYNA is adopted to model the mechanical behavior of the expanded polystyrene (EPS). The model is based on five coefficients: material mass density, Young's modulus, Poisson's ratio, tensile stress cut-off, damping coefficient. The material parameters are reported in Ruggiero et al. (2018).

4. Numerical results and discussion

The described numerical model was validated by comparison with experimental results in Ruggiero et al. (2018) for three different explosive charges (2.1, 6.3, and 10.5 kg) without partitions. Results for 6.3 kg, the reference configurations of the present work, can be summarized as follows.

- On the surface, the damage is confined to the area under the cartridge, generating a crater of about 300 mm in diameter.
- Below the surface, both in the screed, near the waterproof sheet, and in the in-situ-concrete, the damage has a larger extension and this extension is larger in the longitudinal direction (parallel to the ribs) than in the transverse direction. The reason is that stress waves propagate undisturbed along the rib below while their propagation is obstructed by the polystyrene blocks and the discontinuity between two adjacent predalles.
- Damage in the upper region consists in pores compaction due to the compression wave that leads to concrete crumbling; in the lower region, spalling occurs due to the tensile wave generated by reflection of the compression wave at the free surface;
- Regarding the reinforcing elements, failure occurs under the explosive charge into the steel wire nets of the screed and the in-situ concrete.

Similar features are predicted for the two configurations with partitions even if a larger extension of damage in concrete is evident from Fig. 5 and Fig. 6. The partitions, reflecting the blast wave, confine and amplify the loading pressure on the top surface resulting in a greater amount of damage into the slab.

Specifically, on the transverse direction, damage develops mainly into the screed, under a tensile state of stress. For partition parallel to the rib, on the top surface of the slab beyond the partition, a release wave develops, due to the lack of the blast wave push. The superposition of the release wave with the tensile waves coming from other discontinuities (interface with polystyrene blocks and bottom surfaces) determines a more severe tensile state of stress into the slab than in the configuration without partitions. This causes a larger amount of damage in the region beyond the partition, Fig. 5b. In the case of partition orthogonal to the rib, the amplification mechanism due to the release is absent. However, due to the confinement of the blast wave in the same region, more damage is predicted than in the reference configuration, Fig. 5c.

In the longitudinal direction, damage develops mainly into the rib and the predalles. For the partition orthogonal to the rib, the release wave beyond the partition accelerates and amplifies the damage process compared to the reference configuration, Fig. 5c and Fig. 6c. For the partition parallel to the rib, damage occurs later in time. However, sustained by the confined blast wave, damage develops for a greater extension and, for in-situ concrete, closer to the top surface (at the interface between the screed and the in-situ concrete), Fig. 5b and Fig. 6b.

However, the blast wave confinement is not so high to affect the failure of the steel reinforcing elements. In all configurations, failure is confined to the wire nets of the screed and the in-situ concrete.

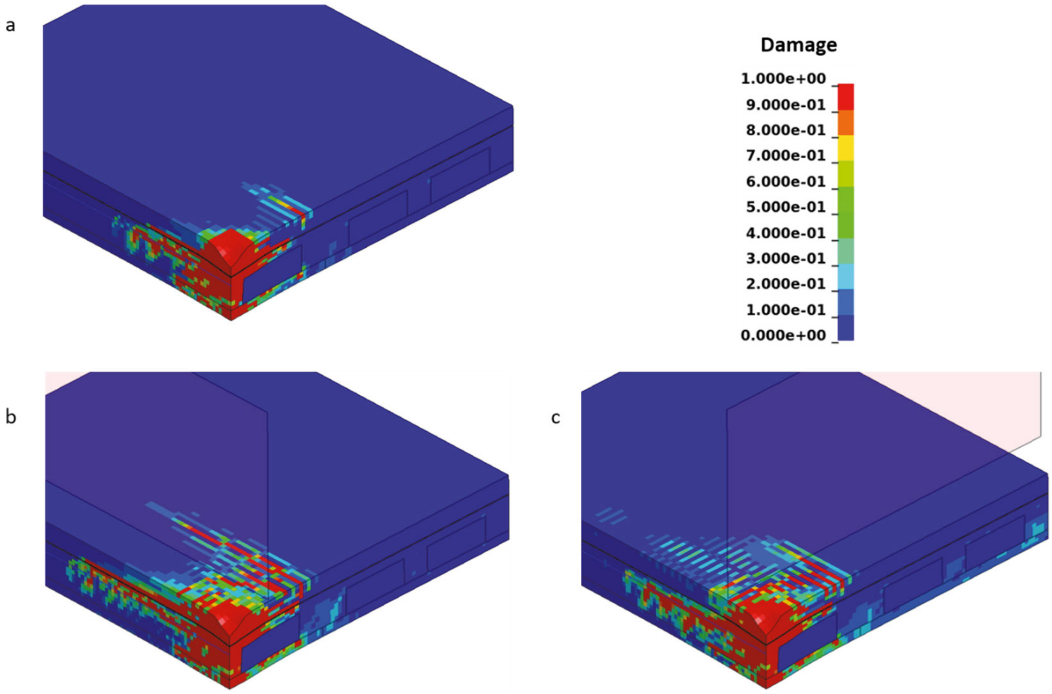

Fig. 5. Top view of damage contours for: (a) reference configuration; (b) partition parallel to the rib and (c) partition orthogonal to the rib.

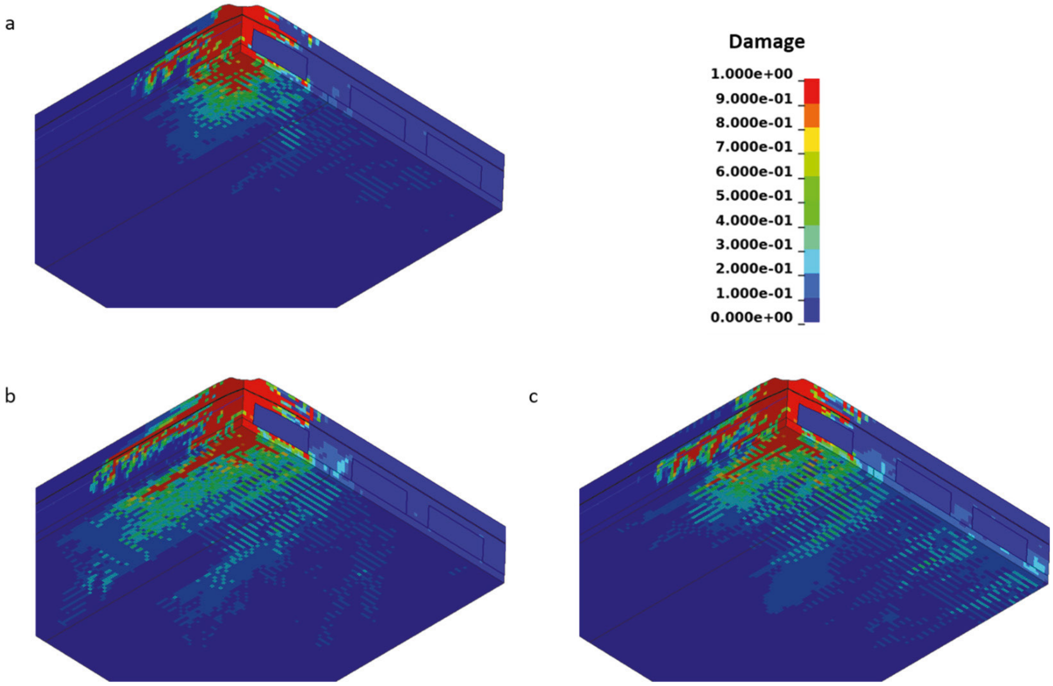

Fig. 6. Bottom view of damage contours for: (a) reference configuration; (b) partition parallel to the rib and (c) partition orthogonal to the rib.

5. Conclusions

In this work, numerical simulations have been performed with the aim to investigate how the presence of partitioning elements influence the blast wave induced damage into slabs used for civil buildings. Two different orientations of the partitions have been analyzed. For both cases, the increase in damage compared to the configuration without partitions have been estimated. Before the partition, increase of damage is due to the blast wave confinement, while beyond is due to the immediate developing of a release wave. The main result of the work is the identification of the mechanisms that determine the damage generation. This result can be potentially exploited to design more effective structures taking into account also the partition elements.

Acknowledgements

The research activity was funded by Rete Ferroviaria Italiana that is gratefully acknowledge also for having allowed to exploit the experimental results for scientific research purposes.

References

Fachinger, J., den Exter, M., Grambow, B., Holgerson, S., Landesmann, C., Titov, M., Podruhzina, T., 2004. Behavior of spent HTR fuel elements in aquatic phases of repository host rock formations, 2nd International Topical Meeting on High Temperature Reactor Technology. Beijing, China.

Fachinger, J., 2006. Behavior of HTR Fuel Elements in Aquatic Phases of Repository Host Rock Formations. Nuclear Engineering & Design 236,

Ngo T., Mendis P., Gupta A., Ramsay J., 2007, Blast Loading and Blast Effects on Structures – An Overview, EJSE Special Issue: Loading on Structures, 76-91.

Wu, C., Oehlers, D. J., Wachl, J., Glynn, C., Spencer, A., Merrigan, M., Day, I., 2007. Blast Testing of RC Slabs Retrofitted with NSM CFRP Plates. Advances in Structural Engineering 10 (4), Multi-Science Publishing Co. Ltd., United Kingdom, 397-414.

Yi, N. H., Kim, J. H. J., Han, T.S., Cho, Y. G., Lee, J. H., 2012. Blast-resistant characteristics of ultra-high strength concrete and reactive powder concrete, Construction and Building Materials 28, 694–707.

Foglar, M., Kovar, M., 2013, Conclusions from experimental testing of blast resistance of FRC and RC bridge decks, International Journal of Impact Engineering 59, 18–28.

Li, J., Wu, C., Hao, H., 2015, An experimental and numerical study of reinforced ultra-high performance concrete slabs under blast loads, Materials and Design, 82, 64–76.

Wang, W., Zhang, D., Lu, F., Wang, S., Tang, F., 2013. Experimental study and numerical simulation of the damage mode of a square reinforced concrete slab under closein explosion, Eng. Fail. Anal. 27, 41–51.

Shi, Y., Chen, L., Wang, Z., Zhang, X., 2015. Field tests on spalling damage of reinforced concrete slabs under close-in explosions, International Journal of Protective Structures 6, 389–402.

Ruggiero, A., Bonora, N., Curiale, G., De Muro, S., Iannitti, G., Marfia, S., Sacco, E., Scafati, S., Testa, G., 2018. Experimental and numerical investigations of blast effects on full-scale concrete slabs. Submitted.

Marfia, S., Bonora, N., Curiale, G., De Muro, S., Iannitti, G., Ruggiero, A., Sacco, E., Scafati, S., Testa, G., 2018. Strengthening solutions for mitigating blast effects in concrete slabs: experimental and numerical study of full-scale frames. Submitted.

LS-DYNA Keyword User's Manual, Version 971, May 2014, Volume I-II, Livermore Technology Software Corporation (LSTC).

Riedel, W., Thom,a K., Hiermaier, S., Schmolinske, E., 1999. Penetration of reinforced concrete by BETA-B-500, in Proceedings of the 9th International Symposiumon Interaction of the Effects of Munitions with Structures, Berlin, 315-322.

Riedel, W., 2000. Beton unter dynamischen lasten meso-und makromechanische modelle und ihre parameter, PhD Thesis, Ernst-Mach-Institute, Freiburg, Germany.

Johnson, G. R., Cook, W.H., 1983., A constitutive model and data for metals subjected to large strains, high strain rates and high temperatures, 7th International Symposium on Ballistics, The Hague, The Netherlands, 541-547.

Mooney, M., 1940. A theory of large elastic deformation, Journal of Applied Physics, 11 (9), 582–592.

Rivlin, R.S., 1948. Large elastic deformations of isotropic materials. IV. Further developments of the general theory, Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences, 241(835), 379–397.