Numerical Prediction of the Dynamic Response of Reinforced Concrete Hollow Core Slabs under Blast Loading

A. Maazoun[12], S. Matthys[1], B. Belkassem[2], R. Mourão[2], J. Vantomme[2]

[1]Ghent University, Magnel Laboratory for Concrete Research, Belgium
[2]Royal Miliatry Academy, Civil and Materials Eng Dept, Belgium

1 Abstract

This paper investigates the use and accuracy of finite element simulations by means of LS-DYNA of reinforced concrete hollow core slabs with a compression layer, simply supported and subjected to blast loading. The aim of this paper is to explain how to develop a numerical model, in order to predict the maximum deflection and crack distribution. Parametric studies related to hourglass energy, erosion value and the material model of the concrete are performed in order to evaluate the effects on the dynamic response of the hollow core slabs. This numerical analysis is completed by experimental tests for validation purposes.

Keywords: Blast loading; Hollow core slab; Hourglass energy; Numerical model; Add-erosion; Dynamic response

2 Introduction

Reinforced concrete (RC) is one of the principal materials used for blast protection due to its strong energy absorption capacity of the blast wave. Understanding the dynamic response of RC structures under blast loading remains a topic of research and discussion, due to the complexity of the problem an additional difficulty is related to the destructive nature of the blast wave. The finite element modelling (FEM) is one of the methods used, especially to predict and understand the dynamic response of RC structures under extreme loading such as blast loads. Castedo et al. [1] tested eight RC slabs under different combinations of explosive mass and standoff distances, the results are validated with numerical models of RC slabs which are able to predict the damage distributions successfully. Xia et al. [2] performed a numerical investigation into the performance of a protective metallic foam cladding on RC structural member using LS-Dyna software. The model is able to accurately predict the behaviour of both foam and slabs under blast loads. The present paper focuses on a numerical investigation of a reinforced concrete hollow core slab (RCHCS) subjected to an explosion underneath it. The aim of this paper is to explain how the numerical model has been established, in order to predict the maximum deflection and crack distribution. A quarter model of the RCHCS is adopted for blast analysis. Parametric studies with respect to hourglass energy, erosion value and the material model of the concrete are performed in order to evaluate the effects on the dynamic response of the hollow core slabs. The numerical models are validated with experimental results.

3 Finite element analysis of reinforced concrete hollow core slabs

3.1 Finite element model

A schematic representation of a RCHCS is shown in figure 1. For the analysis, a quarter model can be considered (fig 2). The numerical model is analyzed for 0.5 seconds, which is the time sufficient for the blast wave to propagate throughout the slab. The run time is 16:23:52 hours. The hollow core slabs are modeled with Lagrangian formulation. The concrete is modeled using constant stress solid elements and for the steel reinforcement consists of Hughes-Liu beam elements. The RCHCS has a thickness of 215 mm, width of 600 mm and length of 6000 mm [3]. The explosive charge of 1.5 kg of C4 is suspended under the slab at a standoff distance of 0.5 m.
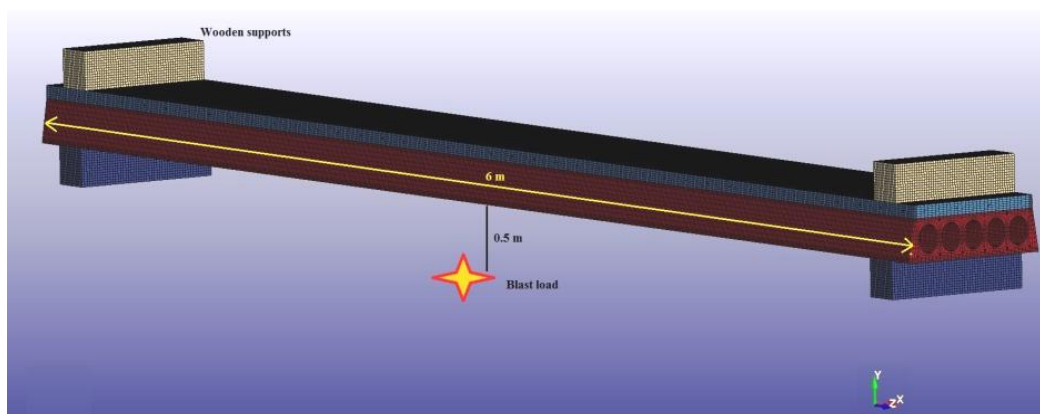
Fig.1:   A schematic representation for the numerical model of RCHCS with compression layer

3.2   Symmetry

Due to the symmetry of the geometry and the blast loading, taking into account the time cost of the simulations, a quarter model is adopted as shown in figure 2.The translation of the nodes in the symmetry planes are constrained by the command boundary SPC-set. This means that two planes of symmetry (XY and YZ) are considered and the nodes in those planes are subjected to the boundary constraints as shown in the table 1.
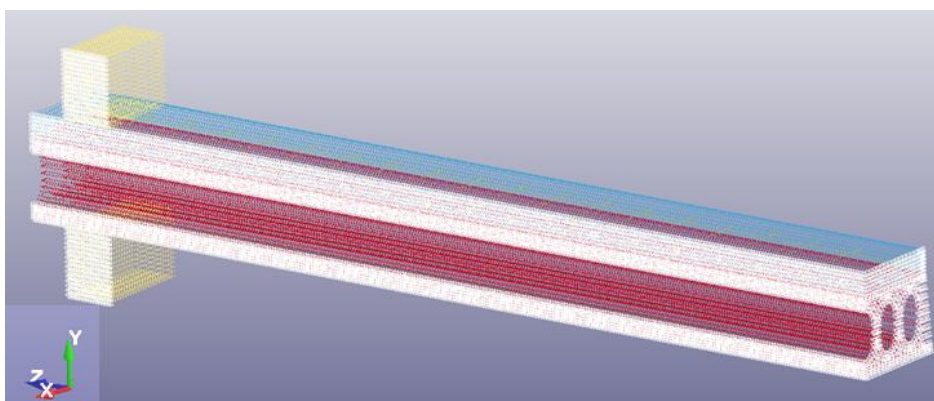

Fig.2:   A quarter model of RCHC with planes of symmetry

Plane of symmetry	x Displacement	y Displacement	z Displacement	φx Rotation	φy Rotation	φz Rotation
XY	Free	Free	Fixed	Fixed	Fixed	Free
YZ	Fixed	Free	Free	Free	Fixed	Fixed

Table 1: Planes of symmetry with boundary conditions

3.3   Material models for the concrete

A wide variety of material models for concrete exist in the LS-DYNA library. In this study two material model of concrete are chosen. The Winfrith concrete model 'MAT084' and the Concrete Damage Release 3 'MAT072R3'. The Concrete Damage Release 3 is a three invariant model that uses three shear failure surfaces and includes damage and strain rate effects, while the Winfrith model is a smeared crack model and smeared rebar model that is implemented in the 8 node single integration point continuum element [5]. Both of these models include the strain rate effects and can predict the local and global response of concrete structures subject to impact and blast loadings. The MAT072R3 model is not able to model crack generation, therefore material add-erosion is used to model the failure. The Winfrith model has a crack generation capability and viewing the cracks is possible using

a post processing command. The input parameters for the used concrete material models are shown in the appendix.

3.4 Materials models for the steel reinforcement

The steel rebars are modeled using material type 24 (MAT_PIECEWISE_ LINEAR_ PLASTICITY). This material model represent steel reinforcement behavior, with plastic deformation, strain rate effects, and failure [5]. A dynamic increase factor (DIF) is applied to the constitutive model, for both yield and ultimate strength of the steel reinforcement. The DIF curve is shown in figure 3 for the strain rate interval 10^{-4} s^{-1} to 1000 s^{-1} .
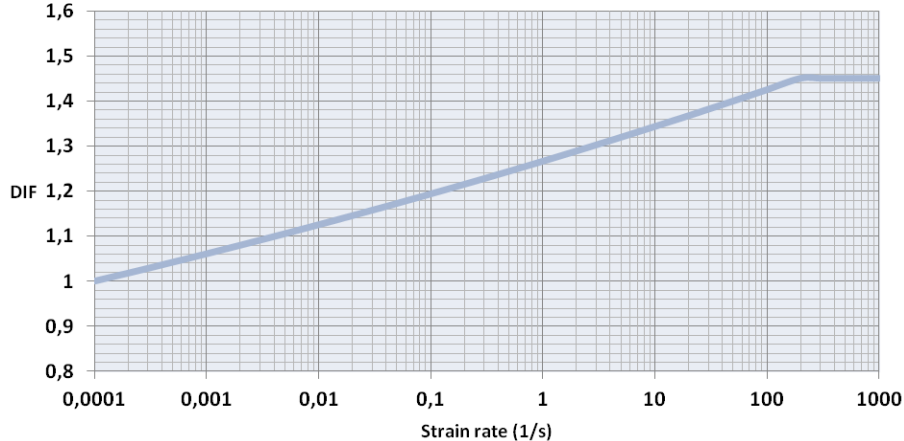

Fig.3: DIF curve for steel reinforcement

3.5 Contact algorithms

To avoid unwanted damage near the supports and to prevent penetration between the supports and the concrete surface during the explosion, a command 'Automatic-Surface-to-Surface' is applied between the supports and the specimen. For blast study, bond slip can be neglected [4] and the reinforcing beam elements can be coupled to the concrete elements through the command 'constrained Lagrange in solid' formulation. Duplicated nodes between the compression layer and the hollow core slab are merged to assume a good interaction and a perfect bond.

3.6 Blast modelling

The blast load can be modeled in LS-DYNA by using three methods, the empirical method, the Multi Material Arbitrary Lagrangian Eulerian (MM-ALE) method, and a coupled version of the empirical and MM-ALE method. In this study, the empirical method is used because it is the simplest approach and requires less time for analysis. This approach requires the mass and coordinate of the explosive to be defined; which is done by means of the command LOAD-BLAST-ENHANCED. The blast wave reached the slab after 0.13 milliseconds and propagated through the slab as a pressure wave. The blast wave reaches the bottom of the slab with a pressure of 47.95 MPa. The reflected pressure and the reflected impulse are shown in figures 4 and 5.
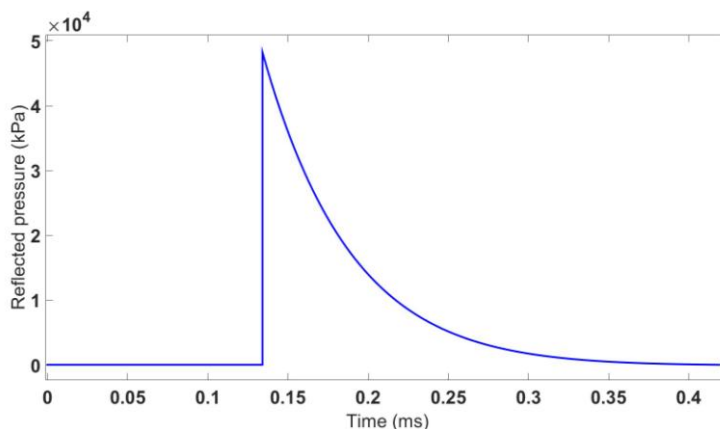

Fig.4: The reflected pressure time histories at the mid span of the bottom of the RC hollow core slab
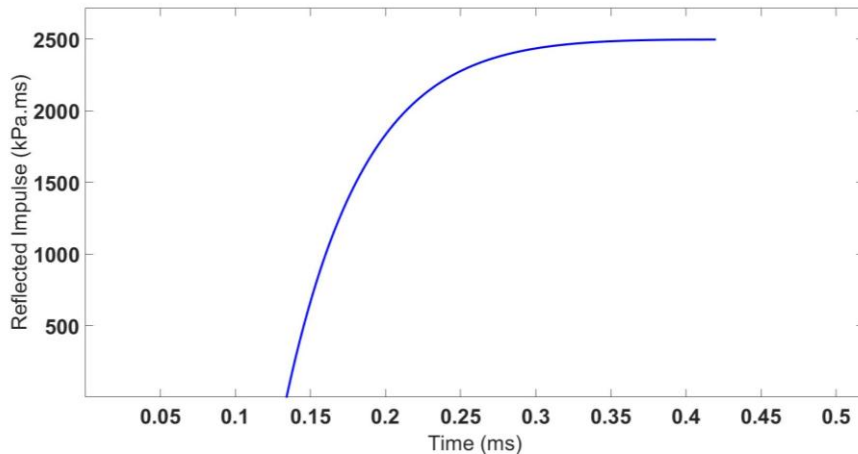
Fig.5:   The reflected impulse time histories at the mid span of the bottom of the RC hollow core slab

4   Parametric study

4.1   The material model for the concrete

The unconfined compressive strength of the RC hollow core slab and of the compression layer are 45 MPa and 30 MPa respectively. The main advantage offered by the MAT072R3 model is that it allows the automatic generation of all the parameters by introducing the unconfined compressive strength and the density of the concrete. The Winfrith model needs in addition also the maximum aggregate size and the fracture energy, if the strain rate is considered. Compared to experimental data, both models for the concrete allow to obtain a fairly good prediction of the maximum deflection at the mid span of the slab. The dynamic response (the oscillation period) of the Winfrith model matches test data somewhat better compared to the MAT072R3model, whereas the latter shows a stiffer response as shown in figure 6.
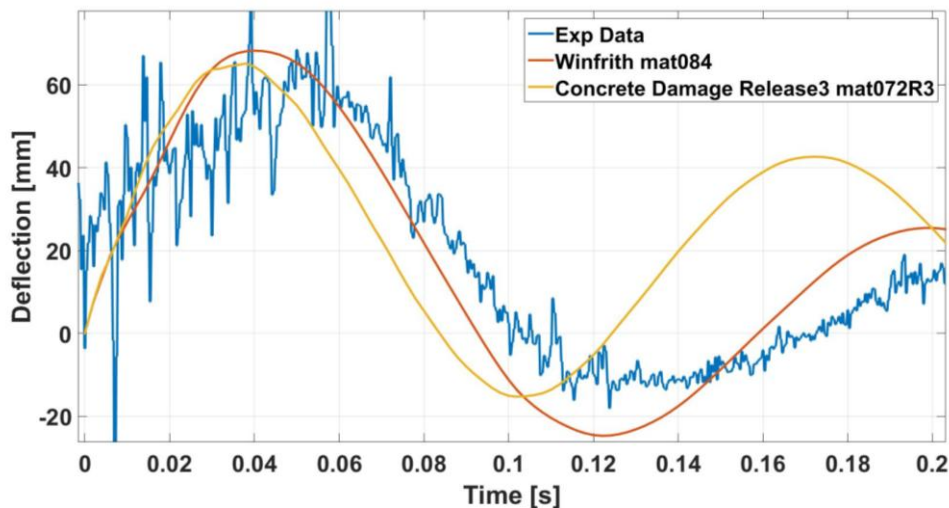

Fig.6:   Displacement time history of nodes located at the mid span of the hollow core slab

Fig 7a Shows the experimentally obtained cracks at the top surface at mid span of the slab. Fig 7b shows the longitudinal crack at mid span of the slab. This distribution of cracks at mid span of the slab is also well predicted by both numerical models (Fig 7c in terms of cracks distribution by the Winfrith model, and Fig 7d in terms of add-erosion for the MAT072R3 model).
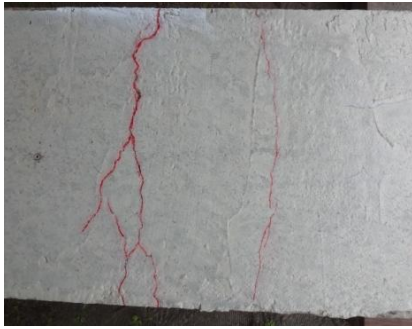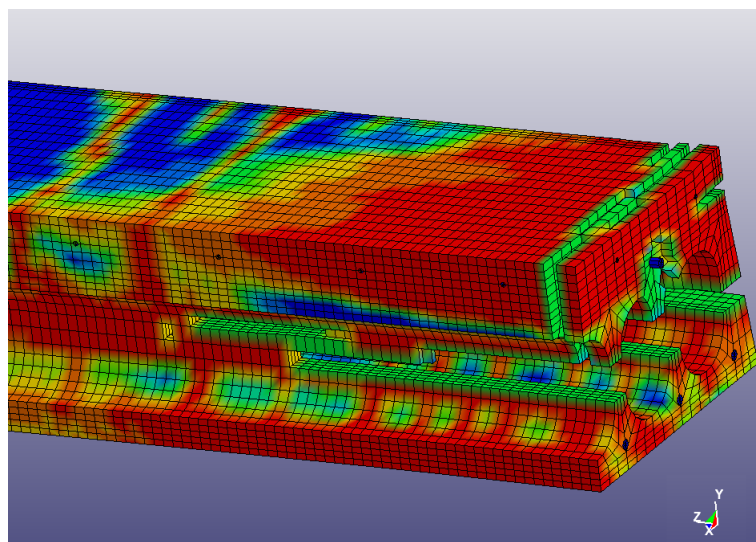
(a) Experimental results on the upper side

(b) Experimental results on the lateral side
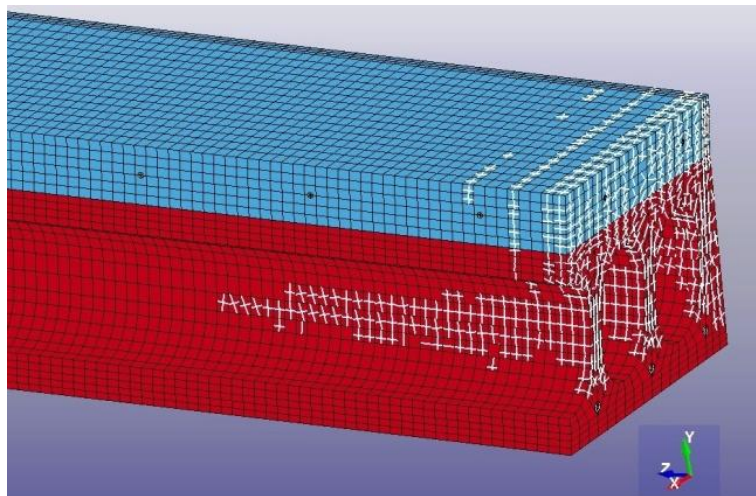
(c) Winfrith model

(d) Concrete Damage Release 3 model

Fig.7: Damage distribution of blasted hollow core specimens

4.2 Effects of the hourglass energy on the maximum deflection

Hourglass (HG) modes are nonphysical deformation modes of the finite element mesh that produce zero strain and no stress. Hourglass modes occur only in under-integrated (single integration point) solid, shell elements [5]. LS-DYNA has various algorithms to counteract the hourglass effect. The procedure is implemented using the command "control-hourglass" which allows to set the type of hourglass countermeasure (viscous or stiffness forms). Viscous forms generate hourglass forces proportional to components of nodal velocity contributing to hourglass modes and inhibits additional hourglassing deformation. The stiffness forms generate hourglass forces proportional to components of nodal displacement contributing to hourglass modes which is able to reduce total accumulated hourglassing deformation. In this study, the hourglass types 1 (viscous form), 4 and 5 (stiffness form) are studied.
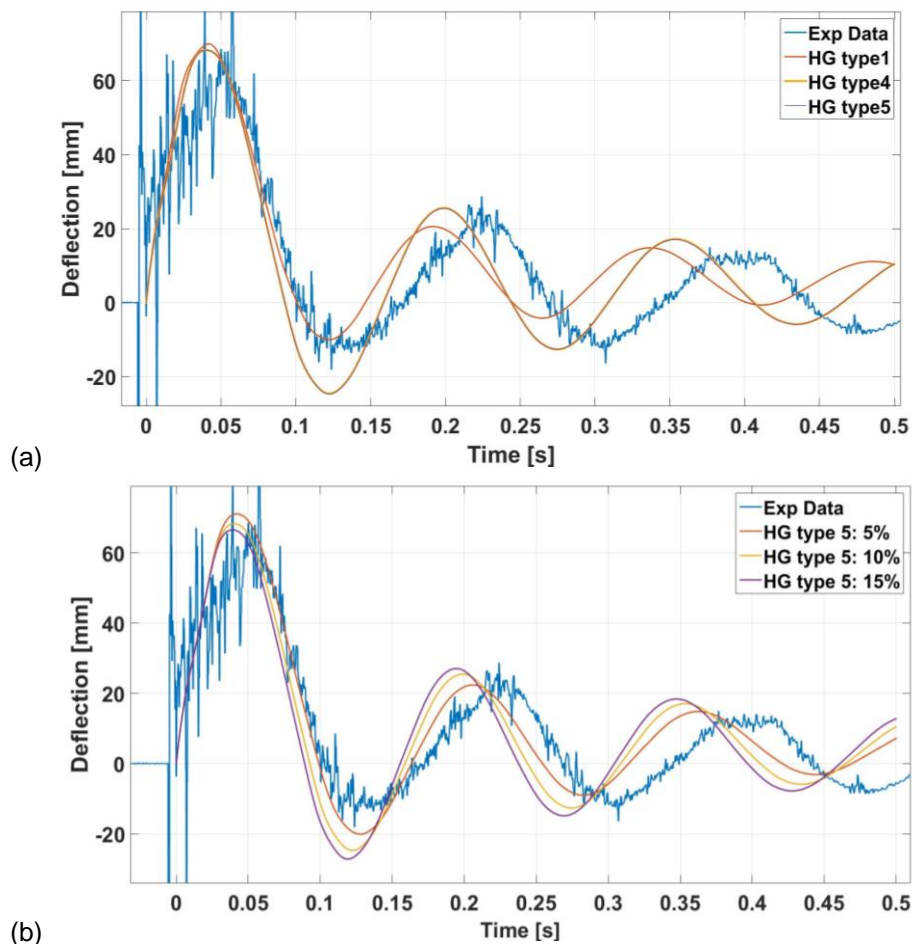
(a)

(b)

Fig.8:   Effects of the hourglass energy on the dynamic response of RCHCS

The simulations show that the selected type of hourglass countermeasure influences the numerical results. The default algorithm (hourglass type 1 with viscous form), which is the cheapest in the calculation time, is generally not the most effective algorithm. The hourglass control types 4 and 5 with stiffness form are utilized with the Winfrith model and it is more effective than the default hourglass control as shown in figure 8a. According to LS-Dyna User's Manuel the hourglass coefficient should not exceed 10%; figure 8b shows that an hourglass coefficient of 5% for type 5 improves the dynamic response of the Winfrith model compared to the experimental data.

4.3   Effects of erosion value

Some of the constitutive models in LS-DYNA, such as the MAT072R3 model for the concrete applied in this study, do not allow failure and erosion. The add-erosion option provides a way of including cracking of the concrete in the numerical model. This option can also be applied to constitutive models that already include other failure/erosion criterions [5]. The erosion option represents a numerical way to delete the elements which satisfy given criteria. The failure criteria should be determined based on a sensitivity study because erosion is not physical parameter [6-7]. In this study, the erosion value is 10% of the maximum effective strain at failure [8]. Figure 8 shows that the erosion value affects the numerical results especially for the MAT072R3 model, whereby the dynamic response of the slab is dramatically changed. For the Winfrith model the erosion value does not affect so much the dynamic response of the slab compared to experimental data.
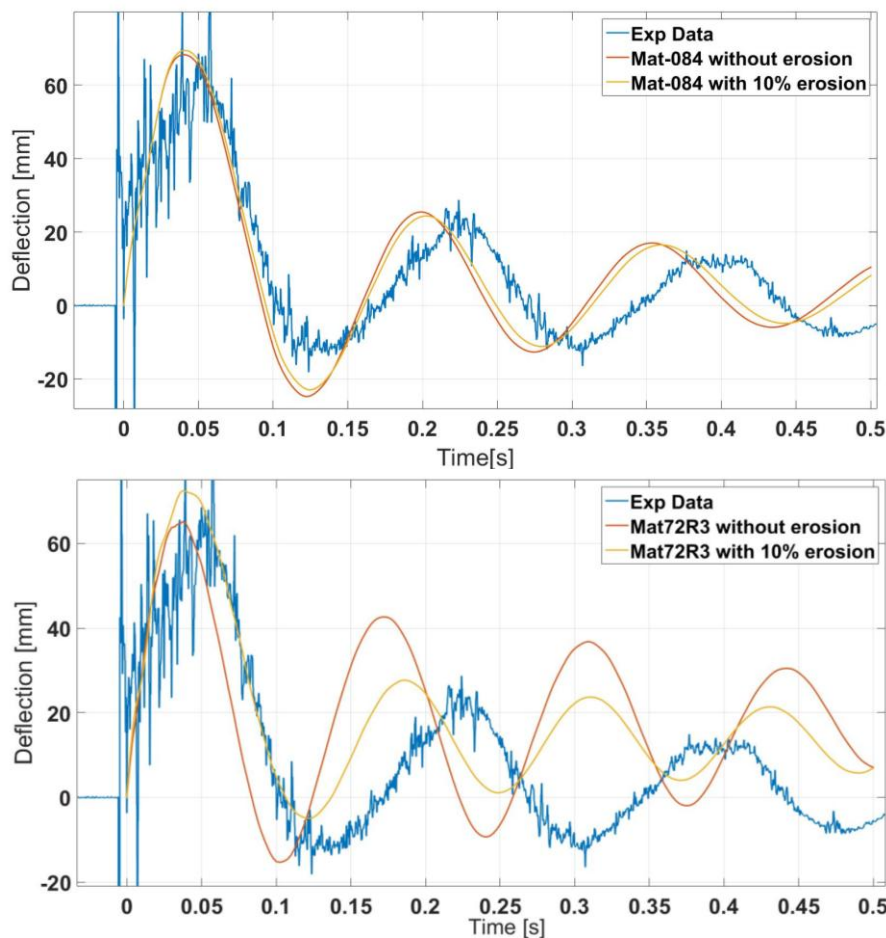

Fig.9:   Effects of the erosion value on the dynamic response of RCHCS

5 Conclusions

This study presents a numerical investigation of RC hollow core slabs with a compression layer, simply-supported, under blast loading. The numerical analysis shows a good agreement with the experimental results for the maximum deflection at the mid span of the slabs and a good prediction of the distribution of cracks. The strain rate effect for concrete and steel are considered in this analysis. The sensitivity studies investigationg the hourglass energy and the add-erosion show that these parameters have a strong effect on the dynamic response predictions of the hollow core slab under blast loading, and should be considered with care. All used material models for concrete have provided good predictions of the maximum deflection. MAT084 is the only model that can provide cracking-specific information in terms of crack size and distribution using a special run command option. For blast studies, the hourglass control type 4 and 5 are more effective than the default hourglass control type 1. The add-erosion value affects the numerical results especially for the MAT072R3 model.

6 References

[1] R.Castedo, P.Segarra, A.Alanon, L.M. Lopez, A.P.Santos, J.A Sanchidrian, "Air blast resistance of full-scale slabs with different compositions: Numerical modeling and field validation", Impact Engineering 86, (2015), 145-156.

[2] Y.Xia, C.Wu, F.Zhang, Z.X. li, T.Benneet, "Numerical analysis of foam-protected RC members under blast loads", Protective Structures-Volume 5.Number4, (2014), 367-390.

[3] A. Maazoun, J. Vantomme, and S. Matthys, "Damage assessment of hollow core reinforced and prestressed concrete slabs subjected to blast loading", X International Conference on Structural Dynamics, EURODYN, (2017),(in press).

[4] L. Schwer," Modeling rebar : The forgotten sister in reinforced concrete modeling", 13th International LS-DYNA® Users Conference, (2014).

[5] LS-DYNA KEYWORD USER'S MANUEL, (2016).

[6] Lee, Hyuk-Kee, and Seung-Eock Kim, "Structural Behavior of SC Panel Subjected to Impact Loading Using Finite Element Analysis", Nuclear Engineering and Design, (2015), 295: 96–105.

[7] Y. S. Tai, T. L. Chu, H. T. Hu, and J. Y. Wu, "Dynamic response of a reinforced concrete slab subjected to air blast load," Theoretical and Applied Fracture Mechanic , vol. 56, no.3, (2011), 140–147.

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

7 Appendix

Example input for the material concrete damage release 3 (Mat-72R3)

```
*MAT_CONCRETE_DAMAGE_REL3_TITLE
Concrete C45/55 72R3
 mid   ro    pr
 1 2300.0000   0.000
 ft    a0    a1    a2    b1    omega    a1f
 0.000 -4.500E+7   0.000   0.000   0.000   0.000   0.000
slambda  nout  edrop  rsize  ucf  lcrate  locwidth  npts
 0.000 0.000000  0.000 39.369999 1.4500E-4   1   0.000   0.000
lambda1 lambda2 lambda3 lambda4 lambda5 lambda6 lambda7 lambda8
0.000  0.000  0.000  0.000  0.000  0.000   0.000   0.000
lambda09 lambda10 lambda11 lambda12 lambda13 b3   a0y   a1y
0.000  0.000    0.000 0.000   0.00   0.000  0.000  0.000
eta1   eta2   eta3   eta4   eta5   eta6   eta7   eta8
0.000  0.000  0.000  0.000  0.000  0.000  0.000   0.000
eta09  eta10  eta11  eta12  eta13   b2    a2f    a2y
0.000  0.000  0.000  0.000  0.000  0.000  0.000   0.000
```

Example input for the material Winfrith (Mat-84)

```
*MAT_WINFRITH_CONCRETE_TITLE
concrete C45/55
 mid  ro    tm    pr    ucs    uts    fe   asize
7  2400. 3.6000E+10 0.2000 5.5000E+7 4.9000E+6 149.  5.00E-3
e    ys    eh   uelong   rate   conm   conl   cont
0.00  0.00  0.00  0.00    0.00   0.00   0.00  0.00
eps1  eps2  eps3  eps4  eps5  eps6  eps7  eps8
0.00  0.00  0.00   0.00   0.00  0.000  0.00   0.00
p1    p2    p3    p4    p5    p6    p7  p8
0.00   0.00   0.00    0.00   0.00   0.00   0.00 0.00
```