A STOCHASTIC SIMPLIFIED SDOF MODEL OF A STEEL BLAST DOOR

UN MODELLO SDOF PROBABILISTICO DI UNA BLAST DOOR DI ACCIAIO

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ABSTRACT

Extreme loads can severely affect civil structures, which are generally not designed with an adequate strength to withstand extreme events. In addition, buildings and critical infrastructures are particularly prone to external man-made bomb attacks. In order to achieve a prescribed level of protection of the building, structural components have to be designed against blast loads. This paper focuses on the design of built-up blast doors made of steel, generally common in storage facilities for ammunitions. Finite Element Analyses (FEAs) are carried out for assessing the behaviour of a built-up door under different levels of detonations. Furthermore, a simplified model accounting for both aleatory and epistemic uncertainties is developed in order to carry out reliability analyses in the future by Monte Carlo (MC) simulations.

SOMMARIO

I carichi estremi possono avere considerevoli effetti sulle strutture civili considerando che queste non sono progettate per contrastare simili eventi. Inoltre edifici sensibili e infrastrutture critiche sono suscettibili ad attacchi di natura terroristica. Per ottenere un adeguato livello di protezione gli elementi strutturali dell'edificio devono essere verificati nei confronti di carichi da esplosione. Quest'articolo focalizza sulla progettazione di "built-up blast doors", generalmente comuni in edifici adibiti a stoccaggio di munizioni. Sono effettuate delle analisi agli elementi finiti (FEAs) per l'accertamento della risposta strutturale della porta sottoposta a diverse detonazioni. Inoltre è sviluppato un modello semplificato con incertezze aleatorie ed epistemiche per eseguire analisi di reliability tramite simulazioni Monte Carlo (MC).

1 INTRODUCTION

Generally all components of a building should be designed against blast loads for achieving a specific level of protection. In a previous work [1] the reliability analysis of a precast concrete wall panel for cladding system has been performed adopting both the conditional and unconditional approach (see for example [2] and [3]). The Fragility Curves (FCs) were developed for all the Component Damage Levels (CDLs). Moreover the unconditional probability of failure was computed for each CDLs by both the FC approach and a single Monte Carlo (MC) simulation, obtaining appreciable results.

In this paper a Stochastic Simplified Model (SSM) for built-up blast doors made of steel is proposed for implementing reliability analyses using MC simulation. The SSM is validated by FEAs using the finite element solver LS-Dyna® [4]. The SSM is conceived to implement both the aleatory and epistemic uncertainties and is based on the equivalence between the two dimensional orthotropic structure of the built-up door and the Single Degree of Freedom (SDOF) system.

The built-up door is subjected to several detonations and the structural response is assessed in terms of support rotation by both the SSM and the Finite Element Model (FEM). The support rotation time histories computed by the two models for each considered blast load are compared and considerations are made on the adoptions of the SSM for carrying out reliability analyses.

In the following section a brief introduction of the built-up blast door is made, while, in Sections 3 and 4 the FEM and SSM are discussed. Finally, in Section 5 the structural response of the built-up blast door subjected to high detonations computed by both the FEM and SEM is presented.

2 THE BUILT-UP BLAST DOOR

Blast doors should be designed to contain an explosion and therefore prevent pressure, fireball leakage and fragment propagation inside the protected area. Generally a blast door is designed to protect personnel and equipment from the effects of external blast loads, something that is similar to the scenario considered in this work.

There are different kinds of blast doors based on their structure, for example single leaf or double leaf, and based on their mode of opening, e.g., vertical lift, and horizontal sliding. There are also several kinds of standard performance classes for categorizing the blast doors according to their function. Performance requirements include:

- Protection for personnel and equipment from external blast pressures resulting from an accidental explosion.
- Prevention of accidental explosion propagation into an explosive storage area.
- Door designed as part of a containment cell which is used in the repeated testing of explosives.
- Door designed as part of a containment structure which is used to protect nearby personnel and structures in the event of an accidental explosion.

In this study a single leaf blast door is considered that should be able to protect personnel and equipment from external blast pressures resulting from an accidental explosion. For this purpose, as performance requirement, the support rotation should be strictly limited to 1 or 2 degrees for avoiding failure and/or blockage of the panic opening system of the door, in a way that both the evacuation of the building and the police/fireman operations can be easily conducted.

The built-up steel door is made by welding steel plates to a steel beam grid, and the exterior plate (thicker than the interior plate) is designed as a continuous member supported by the grid. The grid itself is made by different beams. The beams on the boundaries support the spandrel beams that support directly the exterior plate. Such a built-up door can be considered as an orthotropic plate.

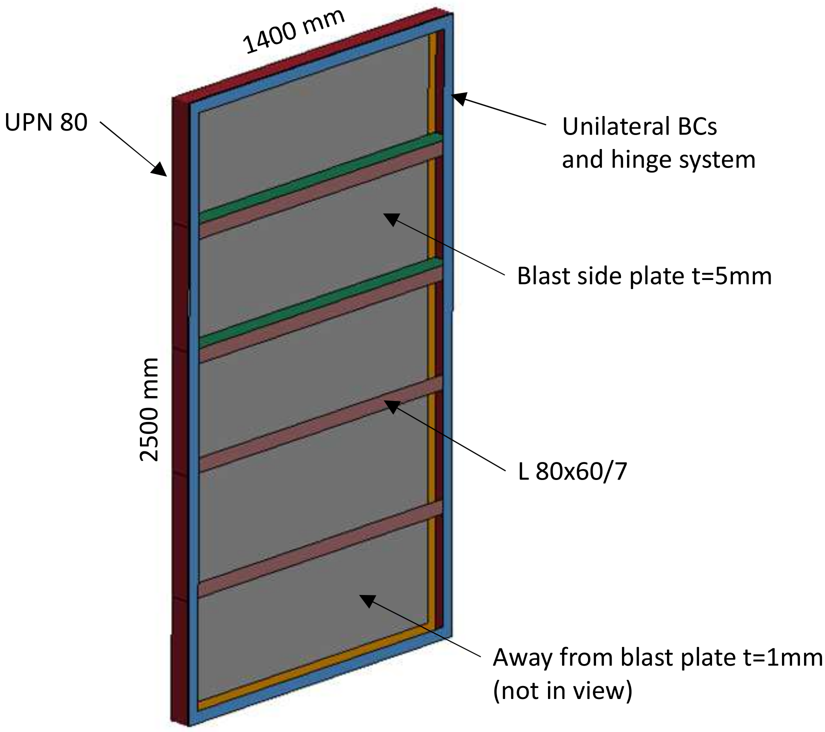


Fig. 1: The built-up door

In Fig. 1 the properties of the built-up door are resumed: the door is 2500 mm high and 1400 mm wide, the exterior plate is 5 mm thick and the interior plate is 1 mm thick. The beams on the boundaries and the spandrels have UPN 80 and L 80x60/7 cross-sections, respectively. The steel used is S275 and by a traction test the actual yielding stress is assessed to be 340 MPa (see Fig. 2), see the acknowledgments section.

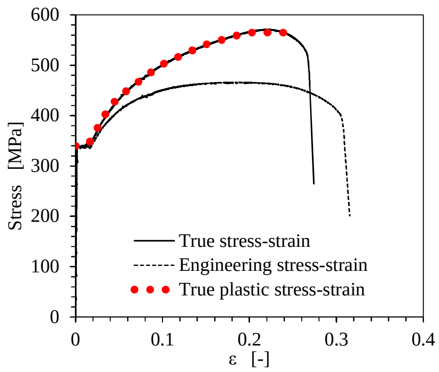


Fig. 2: Steel stress and strain relation

3 THE FINITE ELEMENT MODEL

The FE model is developed by the commercial FE solver LS-Dyna® [4]. It is a three dimensional model consisting of shell elements. The support frame of the door is explicitly modelled for achieving unilateral boundary conditions by contact elements. Moreover, other contacts are provided on the door hinge and door locking system for allowing the rebound response.

The model is made by a total of 84794 shell elements and 85062 nodes. The shell elements are of Belytschko-Tsay type [4] and the contact algorithm is the automatic surface to surface. The detonation occurs at 500 mm from the ground surface and the load distribution is computed by Conwep® [4], so a non-uniform pressure load is considered on the external plate of the door. For the steel, a piecewise linear plasticity model is adopted and the true stress-strain relationship is shown in Fig. 2. Moreover, a fracture criterion is implemented without taking into account the effect of the stress triaxiality on the metal fracture; the fracture occurs when the effective plastic strain reaches 0.2473. The strain rate effect is taken into account by the Cowper and Symonds model [4]; "C" is equal to 500 [1/s] and "p" is equal to 6.

4 THE STOCHASTIC SIMPLIFIED MODEL

The SSM is a SDOF model based on the equivalence of the two-dimensional orthotropic model of the built-up blast door with a SDOF model, which is very common in blast engineering. In this way the SSM is computationally manageable and it is suitable for carrying out reliability analyses by means of MC simulations. In the SSM there are both epistemic and aleatory uncertainties: the epistemic uncertainties are related to errors introduced by the imperfect matching of the two mathematical models, while the aleatory uncertainty is mainly due to the natural variability of the steel yielding stress. The formulas for making the equivalence are provided in [5] and the [6]. It is necessary to compute the moment of inertia (J), and the plastic resisting moment (M_p) of the door sections (the two orthogonal sections). J is computed by assuming as valid the hypothesis of plane sections, considering both the moment of inertia of the spandrels and the transport moment of inertia of the plates. Thus, J is multiplied by the epistemic coefficient α which has a mean value of 1. M_p is computed by J, the dynamic yielding stress (σ_{yd}), and the plastic coefficient (φ). The σ_{yd} is equal to the static yielding stress (σ_y), which is an aleatory random variable, multiplied by the dynamic increase factor (DIF) that has a mean value of 1.19 and is also considered to be variable as a source of epistemic uncertainty. Also φ is handled as uncertain, with a mean value of 1.3. The coefficients of variations are not specified here because for now the SSM is only considered with the mean values of its variables for reasons of comparison with the FEM.

5 RESULTS

The result of the static pushover analysis (by FEM) of the door subjected to a uniform load pressure on the exterior plate is shown in Fig. 3 with the resistance function computed by the SSM. In the case of static resistance function the dynamic increase factor is not considered in the SSM.

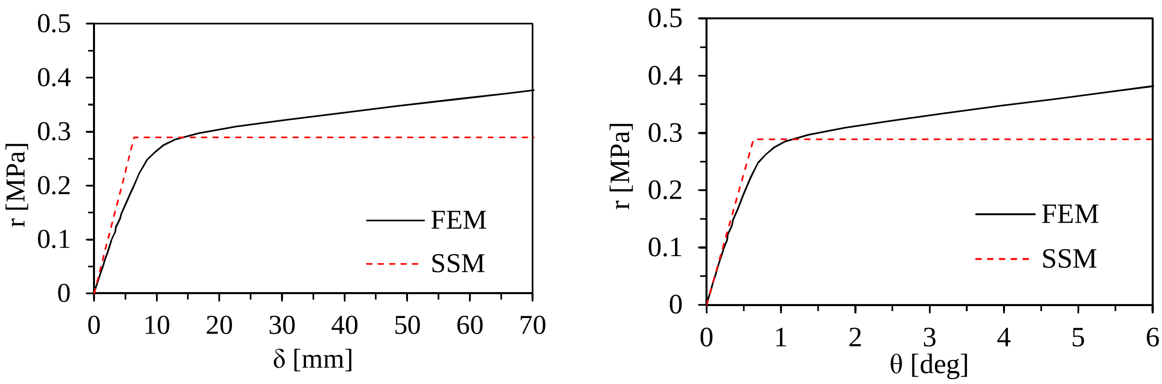
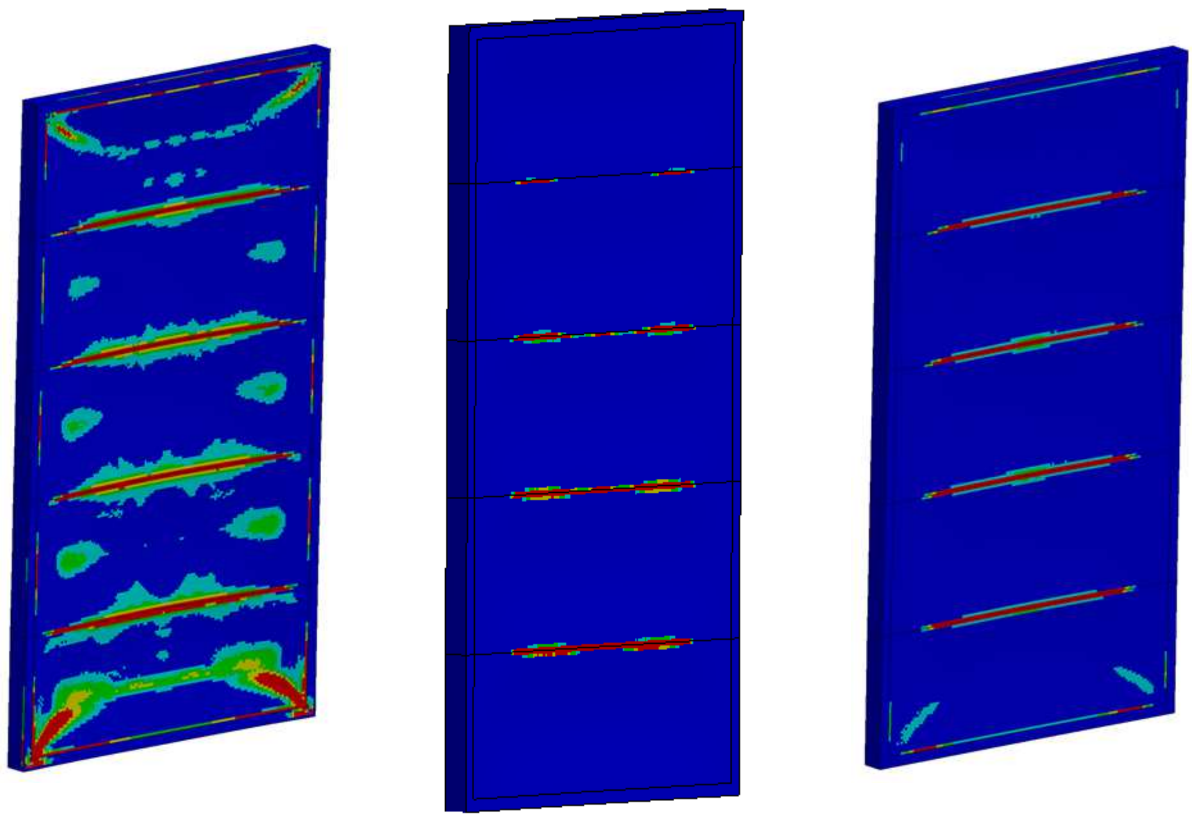
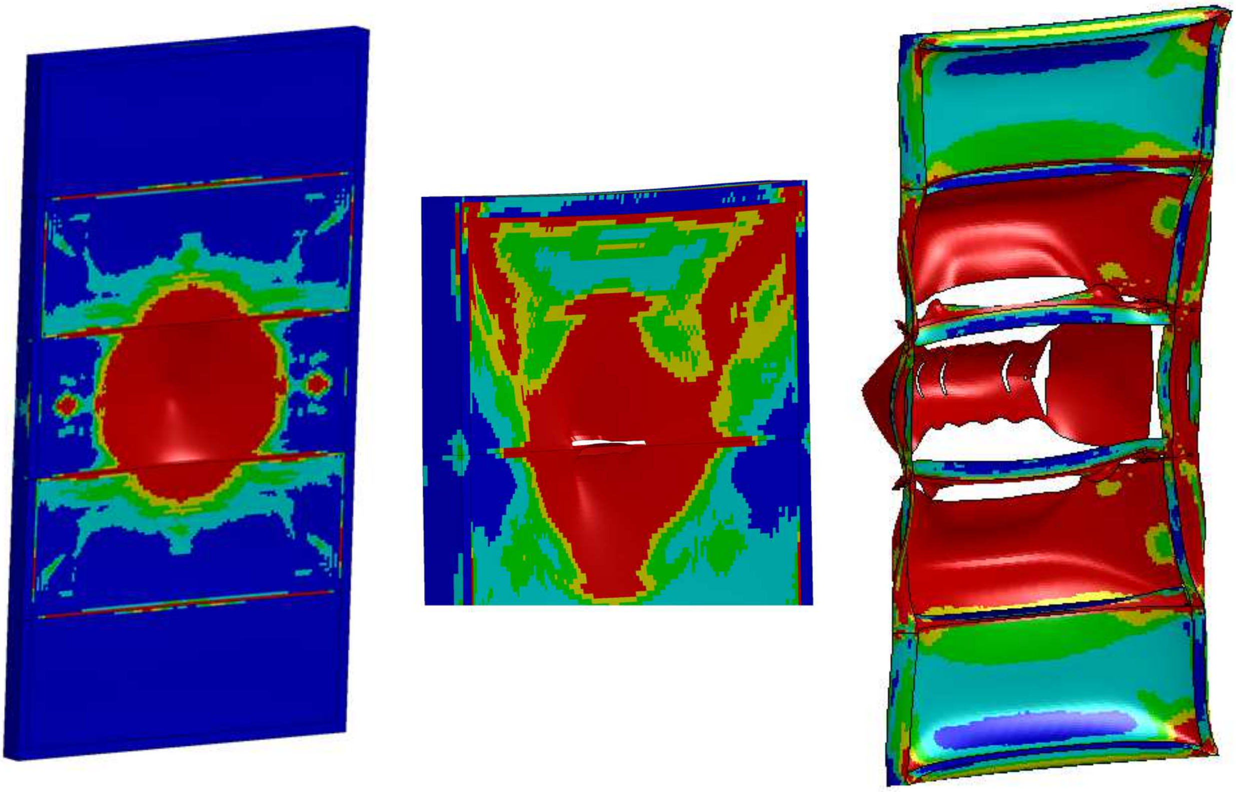


Fig. 3: Static resistance predicted by both the FEM and SSM. δ is the displacement at the mid-span and θ is the support rotation on the shorter dimension of the door

Fig. 3 refers to the support rotations computed on the shorter dimension of the built-up blast door. A good agreement is appreciable especially on the range of 1 and 3 degrees of support rotations that, as previously explained, is the range of interest. For testing the SSM the blast door is subjected to several detonations at a stand-off distance (R) and the prediction of the support rotations are made by both the FEM and the SSM (with the mean value of the stochastic parameters). The explosive (W) is expressed in its TNT equivalent.
In Fig. 4 the results (obtained by the FEM) in terms of plastic strains are plotted for the considered detonations. Instead the effect of close-in detonations [6] (shown in Fig. 4) can be well predicted by the FEM. A close-in detonation leads to a local failure of the blast door causing fractures in the steel plate as shown Fig. 4 and Fig. 5 (R=0.13 m - W=1.18 kg (b)).
The SSM model cannot predict close-in detonations. Furthermore, the structural response of the door subjected to a detonation of 100 kg of TNT at 1 meter of stand-off distance is tricky to predict by the SSM, as can be seen in Fig. 4 and Fig. 5 (R=1 m, W=100 kg). Thus, generally the SSM can predict the structural response of the blast doors for far-field detonations when the blast load can be reasonably considered uniform on the exterior plate. In Fig. 6 the support rotations time history for the considered detonations are shown. Generally the time of the maximum displacement is not captured accurately, but the maximum displacement itself is well predicted considering that the dynamic increase factor is constant in the SSM.
The motion equation of the SSM is solved by SBEDS® [5] (using the explicit solution technique of the average velocity) where the characteristics of the SSM are properly inserted.
The blast load on the FEM and on the SSM is Conwep® based and it is the same for the two models, with the only difference being that on the SSM the load is uniform, while on the FEM it is appropriately distributed on the exterior plate of the built-up blast door.



R=3 m - W=10 kg	R=6 m - W=10 kg	R=6 m - W=20 kg
Chromatic scale: 0 - 0.01	Chromatic scale: 0 - 0.001	Chromatic scale: 0 - 0.001

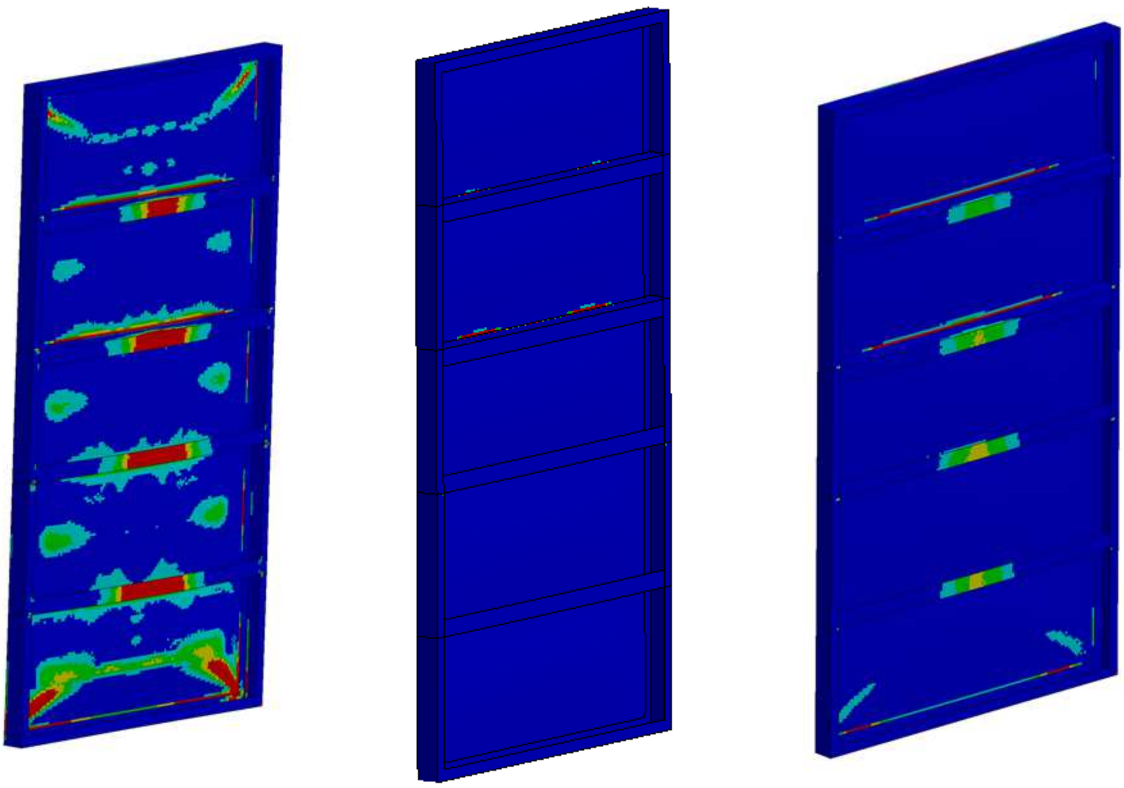


R=0.13 m - W=1.18 kg (a)
Chromatic scale: 0 - 0.01

R=0.13 m - W=1.18 kg (b)
Chromatic scale: 0 - 0.01

R=1 m - W=100 kg
Chromatic scale: 0 - 0.1

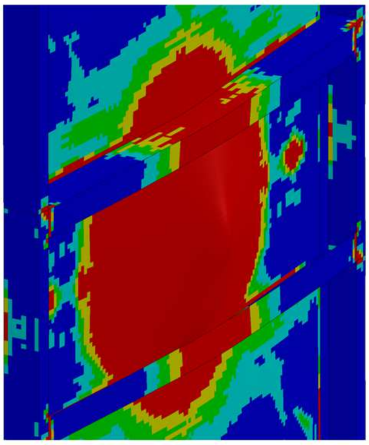
Fig. 4: FEM - Plastic - strain - Front view (blast side) of the built-up door subjected to detonations



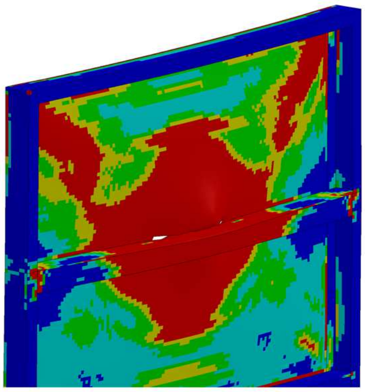
R=3 m - W=10 kg
Chromatic scale: 0 - 0.01

R=6 m - W=10 kg
Chromatic scale: 0 - 0.001

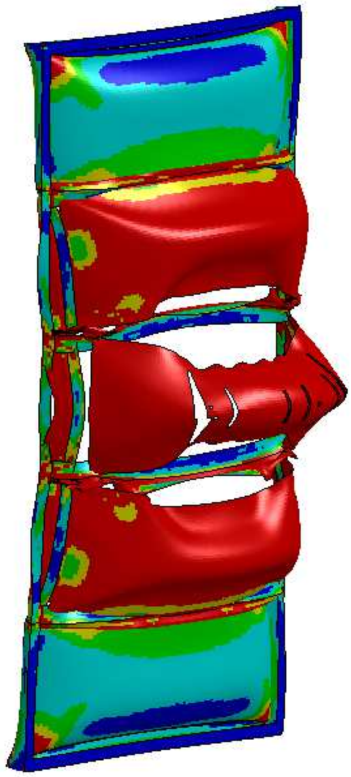
R=6 m - W=20 kg
Chromatic scale: 0 - 0.001



R=0.13 m - W=1.18 kg (a)
Chromatic scale: 0 - 0.01

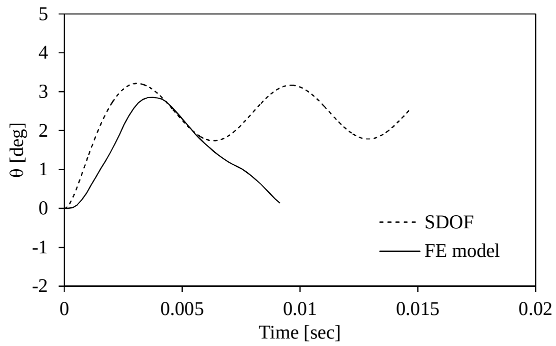


R=0.13 m - W=1.18 kg (b)
Chromatic scale: 0 - 0.01

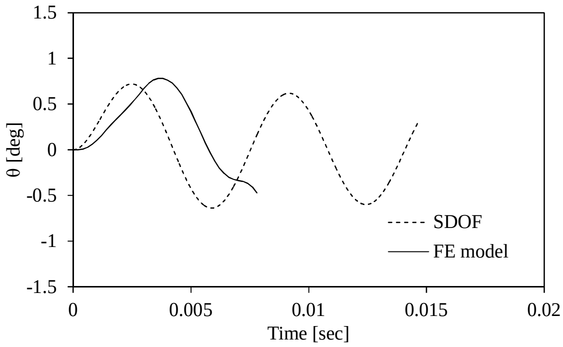


R=1 m - W=100 kg
Chromatic scale: 0 - 0.1

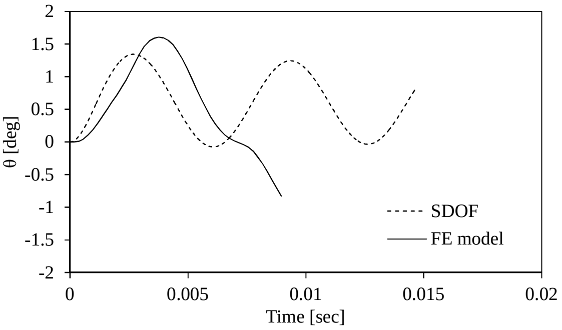
Fig. 5: FEM - Plastic strain - Rear view (away from blast side) of the built-up door subjected to detonations



R=3 m, W=10 kg



R=6 m, W=10 kg



R=6 m, W=20 kg

Fig. 6: Support rotations time histories of the built-up door subjected to detonations

6 CONCLUSIONS

In this study a FEM of a built-up steel blast door has been developed using shell elements. The door is subjected to several detonations and the structural response predicted by the FEM has been compared with the structural response predicted by the Stochastic Simplified Model (SSM) containing both aleatory and epistemic uncertainties. Generally the maximum displacement is reasonably well predicted by the SSM, which can be adopted as the mechanical model for reliability analyses using Monte Carlo simulations. For example the SSM can be utilized for computing the fragility curves point by point using Monte Carlo simulations or for computing directly the probability of failure by the unconditional approach. In both examples a high number of analyses are necessary and a computationally inexpensive mathematical model is mandatory. Moreover, the technique of the SDOF equivalence is common practice in blast engineering [7], so a safety factor developed for this model can become very effective for the design of the blast door. Finally, the SSM allows us to perform reliability analyses by Monte Carlo simulations towards a probabilistic Performance Based Blast Engineering - see for example [8] - where the probabilistic theory developed for the earthquake engineering is extended to wind engineering.

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KEYWORDS

Built-up blast door, blast engineering, finite element analysis, stochastic simplified models, high detonations.