Robustness oriented analysis of structures under extreme loads

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Abstract

The aim of the paper is to present an effective approach for robustness oriented analysis of structures subjected to extreme loads due to explosions or impacts. The main problems concerning the fundamental aspects of the analysis were defined and discussed in details. Limitations of the presented approach were also specified and defined.
To verify the proposed material model for concrete the simple numerical tests were performed and compared with results of experimental tests published in literature. Since this comparison shows the sufficient consistency between the experimental and numerical results, more complex validation analyses were undertaken in order to check the proposed approach in simulation of the real-life situations.
The examples show the usefulness of described method of analysis for problems where the damage pattern is looked for as well as the possible mechanism of failure, in order to assess the necessary level of structural robustness (Diamantidis, [2]). In many practical problems this information is of fundamental meaning, necessary to evaluate the vulnerability of the structure to the blast load and its strength after the partial damage. This issue is extremely important for the assessment of the entire structure robustness based on the analysis of its individual parts.

Keywords: concrete, damage, steel structures, finite element methods, impact

1. Introduction

A realistic evaluation of the structural response due to blast load is a task of timely and growing importance in many engineering situations, no longer confined to classified areas of defence technology. The growing threat of terrorist attacks, industrial incidents, and transport collisions (cars, airplanes, etc.) must be taken into consideration in the design process, especially for important structures located in areas of possible threat.

In order to obtain reliable results from numerical analysis, the rate - dependent plastic - damage constitutive model for concrete has been applied, based on considerations presented by Faria and Oliver [3]. The main goal of the choice of material model was to obtain the relatively simple algorithm, reliable and easy to implement into commercial finite element computer code.

The model has its own point of departure on the continuum damage mechanics [6,7], which is a very powerful and consistent theory that is based on the thermodynamics of irreversible processes. Nonlinear mechanisms of degradation of concrete under tensile or compressive loading conditions are characterized by two independent scalar internal damage variables. This option deals with tensile and compressive concrete behaviour in a unified fashion, where the same material model is adopted for any load combinations. Rate dependency, a very important factor in the analysis of blast loaded structures, has been accounted for as an almost natural extension to the plastic-damage model, introducing a viscous regularization of the evolution laws for the damage variables

The analysis of damages developed in a structure under certain load allows for definition of robustness level defined as insensibility of a structure to local failure [2].

2. Implementation into FEM code

The assumed material model has been implemented into the computer code Abaqus/Explicit as a user subroutine. In order to verify the assumed material model numerical simulation of the experimental test performed by Schenker at al. [8] has been carried out. In this experiment, the permanent damages developed in a thick plate by a far-field explosion of large PETN charge (980 kg) were examined. Load due to the explosion has been modelled as a field of pressure variable in time. For such simple geometry, consisting of the relatively rigid flat surface loaded by a contact explosion, Henrych's [4] empirical formula was introduced. This approach is only applicable for rather simple geometry structures, where the effects of blast wave reflection and their consequent interaction are not so significant (Cichocki, [1]).

Although the assumed discrete model of entire phenomenon was relatively simple, with necessary assumptions concerning the blast wave propagation, the contact between the structure and a subsoil, as well as the influence of heat produced during explosion, the results of numerical analysis carried out using assumed material models for concrete and steel were quite consistent with experimental data. This allows for use of implemented material model in various complex problems concerning blast-loaded structures.

The mechanism of permanent damage was studied in details, in order to evaluate the measures necessary to achieve the needed level of structural robustness of various structures. The results and conclusions may be applied in practical considerations concerning the cost-benefit analysis (JCSS, [5]). Precise and unequivocal description of damages developed in the structure under blast load are necessary for this analysis, where the loads leading to the total collapse of the structure have to be defined.

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3. Numerical analysis

The main goal of this study was to investigate the behaviour of selected structural elements subjected to extreme loads. Among many factors influencing the analysis, one of the most important is the material modelling. Although there is great variety of material models for concrete and steel available in literature, the choice of the material formulation is difficult. The decision should take into account the physical nature of the modelled phenomenon, static or dynamic behaviour, possible rate of deformation, etc. For this reason, the relatively simple, scalar damage model has been chosen, modified, and implemented. Despite its simple formulation which neglects many important features of material behaviour under impulsive loads, the obtained results show its usefulness for practical applications.

The example of results of numerical simulations performed with implemented material model for concrete is presented below. Figure 1 shows the final distribution of tensile damages for a concrete element subjected to a far-field explosion, calculated in the framework of this study. Scalar coefficient (DAMAGET) is equal 1.0 (red colour) for the totally damaged material in tension, and 0.0 for undamaged material (blue colour). The shape, number and depth of the damaged elements were similar to experimental results obtained by Schenker [8], and the observations of other researchers [1]. In order to define precisely the extent of damages developed in material of the structure the entire set of final results should be studied, with special attention focused on damage coefficients calculated separately for tension and compression.

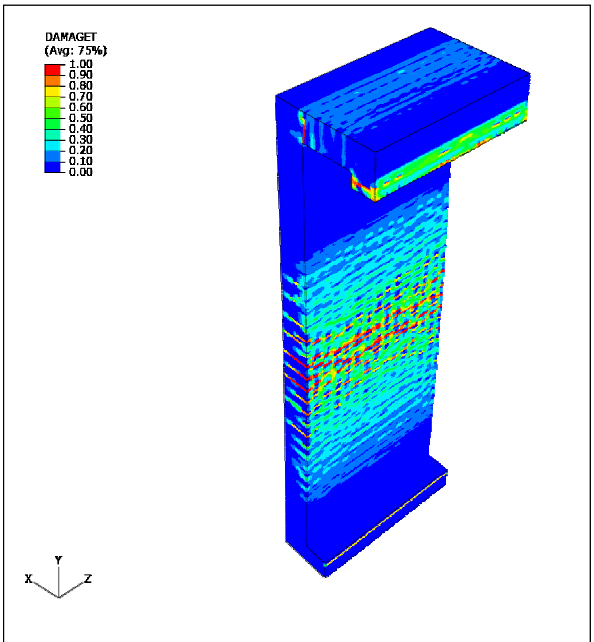

Figure 1: Distribution of damage coefficient (tension).

Regarding the validation of the assumed material model, the main problem is the lack of detailed experimental data, particularly for impulsive loads of great intensity (e.g., explosions, collisions). In most cases, only the final damaged geometry of the structure is studied. With no data about the development of damages over time, the material models' calibration and verification is extremely difficult.

Analysing the results of numerical simulations of the dynamic response of the structure subjected to a blast load, one can notice that the first permanent damages are developed for relatively small values of maximum pressure exerted by the impacting blast wave. In this case the damages will not reduce significantly the robustness of the whole structure, which is still able to carry out the designed loads.

Increasing the load intensity (i.e. increasing the explosive charge, or reducing the distance to the centre of explosion), the permanent damages also increase significantly. They change their extent and distribution, from initial narrow strips to final large parts of completely damaged material. In each stage of analysis the total robustness of analysed structure was evaluated in terms of its entire robustness.

4. Conclusions

The approach presented in this study allows for evaluation the robustness of entire structure subjected to a defined type of load. In this case only a load produced by a far-field explosion has been considered, but other types of loads are also possible to be introduced and analysed. Applied methodology is consistent with one proposed by Joint Committee of Structural Safety ([5]), and developed by COST Action TU0601 "Robustness of structures" ([2]).

Such kind of analysis allows for precise definition of load intensity (separately for each type of load, and for their arbitrary combination) leading to the loss of structural robustness, and consequently to the structural collapse.

Although this problem was studied qualitatively in many elaborations, there was a lack of exact solution, in terms of load level (i.e. intensity) and corresponding distribution of damages.

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