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STIFFENED PLATES SUBJECTED TO UNIFORM BLAST LOADING

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Abstract. An investigation has been carried out to examine the behaviour of stiffened plates subjected to uniform blast loading. The aim of this work is to determine the dynamic response of the plates with different stiffener configurations and consider the effect of mesh dependency, loading duration, and strain-rate sensitivity. Numerical solutions are obtained by using the finite element method and the central difference method for the time integration of the non-linear equations of motion. Special emphasis is focused on the evolution of mid-point displacements, and plastic strain energy. The results obtained allow an insight into the effect of stiffener configurations and of the above parameters on the response of the plates under uniform blast loading and indicate that stiffener configurations and time duration can affect their overall behaviour.

Keywords: blast loading, plates, stiffeners, mesh density, strain-rate sensitivity, time duration.

1. Introduction

Due to different accidental or intentional events, the behaviour of structural components subjected to blast loading has been the subject of considerable research effort in recent years. To provide adequate protection against explosions, the design and construction of public buildings are receiving renewed attention of structural engineers. Difficulties that arise with the complexity of the problem, which involves time dependent finite deformations, high strain rates, and non-linear inelastic material behaviour, have motivated various assumptions and approximations to simplify the models. These models span the full range of sophistication from a simple single degree of freedom systems to general purpose finite element programs such as ABAQUS, ANSYS, and ADINA etc. Schubak *et al.* (1989a) have presented a simplified rigid-plastic method for modelling beams. This work was extended to asymmetric beam sections and subsequently to one-way and two-ways orthogonally stiffened plates (Schubak *et al.* 1989b; Schubak 1991). In this work, the response of a one-way stiffened plate under intense loads, and the stiffened plate was treated as a single symmetric beam with the plate acting as a large flange. The two stiffened plates are then modelled as a grillage of beams with asymmetric section. The rigid-plastic and finite element methods were combined for the modelling orthogonally stiffened plates (Olson 1991). The rigid-plastic modelling used a beam grillage representation of the stiffened plate, wherein the beam sections were asymmetric. In connection with structural dynamics analysis, there are several simple single degree of freedom methods in the classical books of structural dynamics (Biggs 1964; Clough and Penzien 1975). For a more rigorous analysis, the structure must be modelled as a system with multiple degrees of freedom (Louca and Harding 1996). In (Yuen and Nurick 2003) the results of numerical work on built-in quadrangular plates with different stiffener configurations under blast loading were presented. Both temperature-dependant material properties and strain-rate sensitivity were included in the numerical modelling. A numerical modelling was conducted in (Jacinto *et al.* 2001) on metallic plates subjected to explosive loads. A linear dynamic analysis of the plate models with ABAQUS was carried out. Suggestions were made about computational modelling of structures under explosive loading. In (Louca *et al* 1996) results of the response of a typical wall and a tee-stiffened panel subjected to hydrocarbon explosions with geometries typical of those used in offshore structures were presented. Non-linear finite element analyses were performed, accounting for the effect of plasticity, strain-rate and buckling. Comparisons were made between the numerical results and experimental data and the approximate solutions obtained with a single degree of freedom model. Numerical studies of stiffened plates subjected to hydrocarbon explosions and a parametric study of the simplified model of the stiffened plate considering different response aspects including the contribution of stiffeners under different stress state and loading conditions were presented by Pan and Louca (1999).

The main conclusions of these studies are that the boundary conditions have a significant influence on the response and the contribution of stiffeners is influenced by many factors, especially the second moment of inertia of the section. Other investigators have performed similar analyses (Xu *et al.* 1991; Nurick *et al.* 1995; Pan *et al.* 1997; Rudraptana *et al.* 1999).

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In addition, extensive experimental studies have also been conducted to assess numerical simulations (Yuen and Nurick 2003; Jacinto *et al.* 2001; Pan and Louca 1999; Jacob *et al.* 2004; Turkmen and Mecitoglu 1999). Stiffened plates are among the most common structural elements. Stiffeners may be positioned facing towards or away from the blast loading. Stiffeners in the former case are usually termed as in compression and the latter in tension. The contribution of the stiffeners is influenced by many parameters including stress state, loading levels and fixing details. In spite of the large number of plates designed and built, the effects of their details on their behaviour under blast loading are not always well understood or properly taken into account. The numerical results presented in this paper can help obtain design guidelines of off-shore topsides and steel bridge plated structures since explosive tests are costly and dangerous, their reproducibility is not always ensured and the results of the tests always show some degree of uncertainty.

2. Description of the plates

All the plates are 16 mm thick and 1200×1200 mm^2 with rectangular stiffeners 30 mm thick and 70 mm height. In Fig. 1, are shown the different stiffener configurations used in the numerical studies.

3. Finite element modelling

Finite element analysis is performed using the general purpose finite element code ABAQUS/EXPLICIT (Hibbitt, Karlsson and Sorensen 1998), which can incorporate non-linear geometry, strain-rate sensitivity, and thermal effects.

3.1. Model geometry

ABAQUS offers an element library for a wide range of geometric models. In the present study, the fourth noded shell element S4R with reduced integration and hourglass control was used to model the geometry of the plates and stiffeners. Three different models consisting of grids of shell elements of size 0.03; 0.06 and 0.12 representing fine, medium and coarse meshes respectively, were used to verify the accuracy of the finite element models of the plates.

3.2. Idealisation of blast loading

The pressure time-history of a blast wave can be illustrated with a general shape as in Fig. 2(a). The illustration is an idealization for an explosion in free air.

The pressure time-history is divided into a positive and a negative phase. In the positive phase, maximum overpressure, P_s^+, is developed instantaneously and decays to atmospheric pressure, P_0, in the time T^+. For the negative phase, the maximum negative pressure, P_s^-, has much lower amplitude than the positive overpressure. The duration of the negative phase, T^-, is much longer compared to the positive duration. The positive phase is more relevant in studies of blast wave effects on structures because of its high amplitude of the overpressure and the concentrated impulse i^+, which is the area under the positive phase of the pressure – time curve.

The pressure time-history in Fig. 2(a) can be approximated by the following exponential form Eq (1) (Buslon 1997),

$$P(t) = P_0 + P_s^+\left(1-\frac{t}{T^+}\right)e^{-bt/T^+}, \tag{1}$$

where $P(t)$ is the overpressure at time t, and T^+ (the positive duration) is the time required for the pressure to return to atmospheric pressure, P_0.

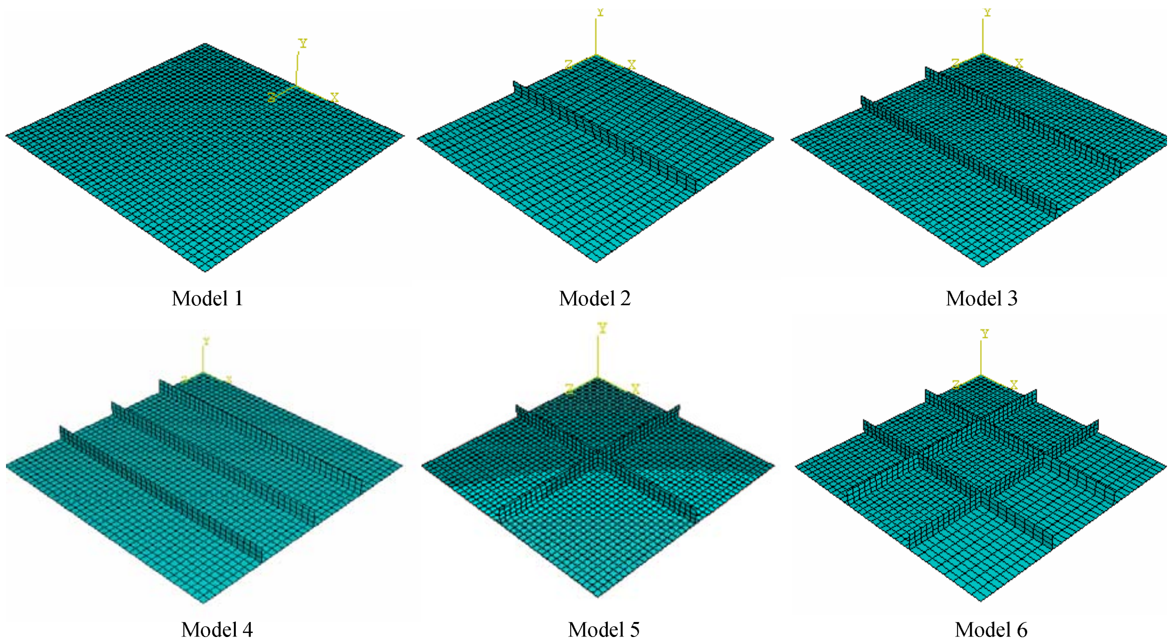

Fig. 1. Configurations of stiffeners

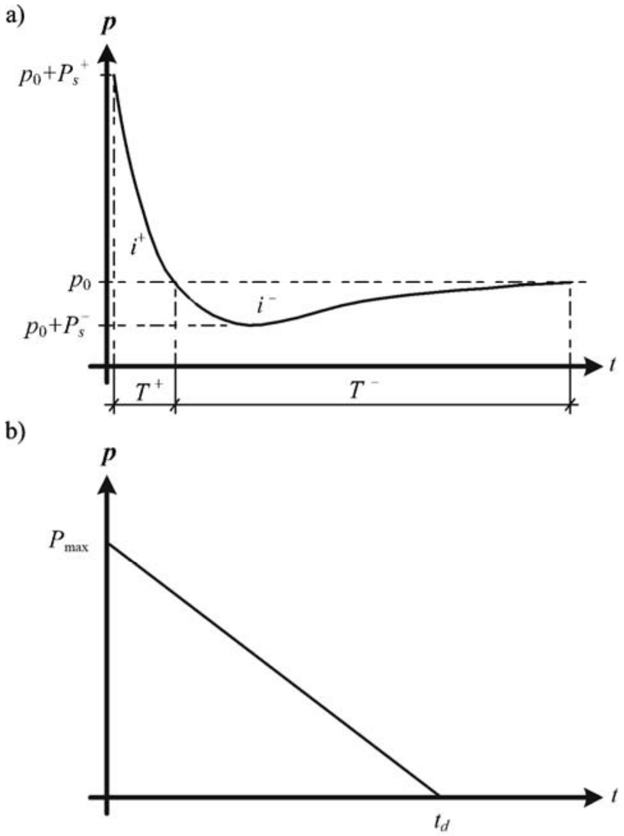

Fig. 2. Pressure time history from a blast: a) exponential form, b) triangular form

Depending on the value of b, various pressure time-histories can be described. The peak pressure, P_s^+, is dependent on the distance from the charge and the weight of the explosives. In addition, if the peak pressure, the positive impulse and the positive time duration are known, the constant b can be determined, and then the pressure time-history is known.

Eq (1) is often simplified by a linearly decaying pressure-time history (Fig. 2(b), Buslon 1997):

$$P(t) = P_{\max}\left(1-\frac{t}{t_d}\right). \quad (2)$$

Conventional high explosives tend to produce different magnitudes of peak pressures depending on the material shape, the number of explosive items, explosive confinement, nature of source and the pressure range being considered. To have a basis for comparison, the explosive energy of the effective charge weight of these high explosives is related to the explosive energy of an equivalent weight of a spherical charge of TNT explosive.

With a scaling parameter Z, Eq (3), it is possible to calculate the effect of an explosion as long as the equivalent weight of charge in TNT is known.

$$Z = \frac{R}{W^{1/3}}, \quad (3)$$

where R is the distance from the detonation and W is the equivalent mass of TNT.

3.3. Material properties

The adopted material properties, as specified in CCM (1997), were Young's modulus, $E = 210$ GPa, Poisson coefficient, $\nu = 0.3$, and density $\rho = 7800$ kg/m^3. The static yield stress was $f_y = 300$ MPa and the average rupture strain $\varepsilon_r = 35\%$. The stress-strain curves were converted into true stress and logarithmic plastic strain according to ABAQUS/EXPLICIT code manual.

4. Dynamic analysis

The dynamic equilibrium equations have been integrated with the central difference scheme with automatic time stepping. The loading function shown in Fig. 1(b) is scaled such that $P_{\max} = 1{,}3$ MPa. In order to study the effect of time duration, four time intervals, t_d have been used in this study 1 ms, 2 ms, 10 ms and 20 ms.

A modal analysis has been conducted to obtain the natural frequencies of the plates for determining the ratio of the duration of the loading over the natural period of the structure. The first frequency of each structure is shown in Table 1 and is for mesh 1.

5. Results and discussions

Unless otherwise specified, all comparisons are made with reference to the fine mesh, mesh 1.

5.1. Effect of stiffeners configurations

For the time duration $t_d = 20$ ms (Fig. 3), the introduction of stiffeners decreases the mid-point displacement significantly; the mid-point displacement for the model 1 is 52.98 mm, while for models 2, 3, 4 and 5 it is 39.48 mm, 36.6 mm, 32.36 mm, and 32.70 mm, respectively. For model 6, the mid-point displacement is 25.30 mm.

Thus, the configurations of stiffeners can have an important influence on the response of the stiffened plates. The same conclusions apply to $t_d = 1$ ms (Fig. 4). The results obtained are in good agreement with the numerical and experimental results. Yuen and Nurick

Table 1. Fundamental frequencies and periods

Model	1	2	3	4	5	6
F_n (cycles/s)	99.84	143.76	152.50	161.97	163.82	177.63
T_n (s)	0.01	0.007	0.0066	0.0062	0.006	0.0056
$T_n/2$ (s)	0.005	0.0035	0.0033	0.0031	0.003	0.0028

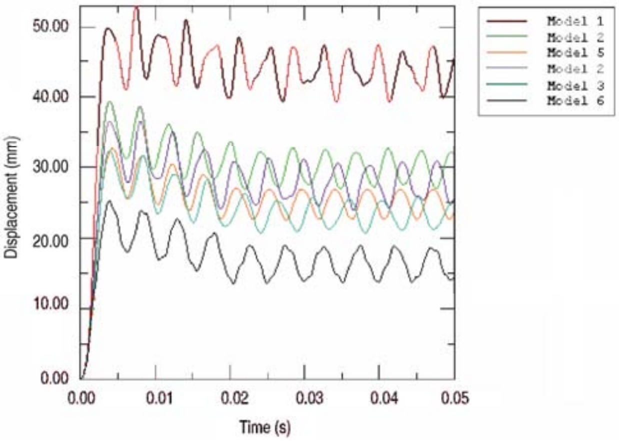

Fig. 3. Influence of stiffener configurations $t_d = 20$ ms

(2003) have stated that as the plates become stiffer (with the addition of more stiffeners), the maximum displacement decreases. Pan *et al.* (1997) found that stiffeners can have a significant effect on global displacement. Turkmen and Mecitoglu (1999) concluded that stiffeners reduce the peak strains by 11 to 42%.

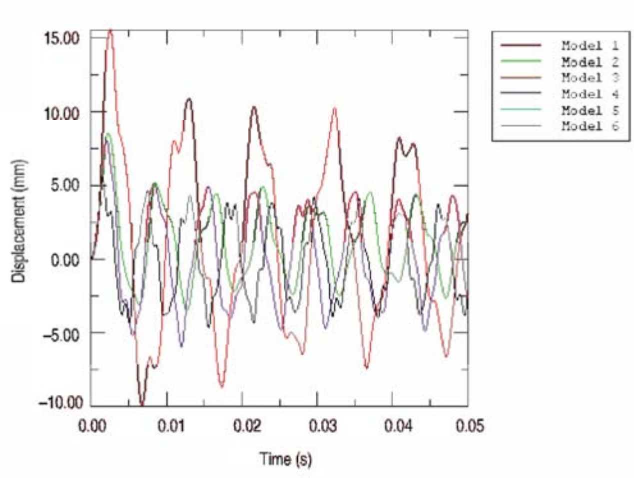

Fig. 4. Influence of stiffener configurations $t_d = 1$ ms

5.2. Effect of time duration

For model 1 ((unstiffened plate)) increasing the time duration by factors of 2, 10, and 20 results in an increase in the mid-point displacement by a factor of 1.73; 3.06, and 3.4, respectively (Fig. 5). For model 2 (plate with a central stiffener) increasing the time duration by a factor of 2, 10 and 20 results in an increase in the mid-point displacement of 1.94; 4.19, and 4.60 (Fig. 6). One important point should be noted, if the time duration t_d is longer than $T_n/2$, then the maximum deformation occurs during the pulse phase, while, on the other hand, if t_d is less than $T_n/2$, the maximum deformation occurs during the free vibration phase and is mainly controlled by the time integral of the pulse, which is in agreement with Chopra (2001).

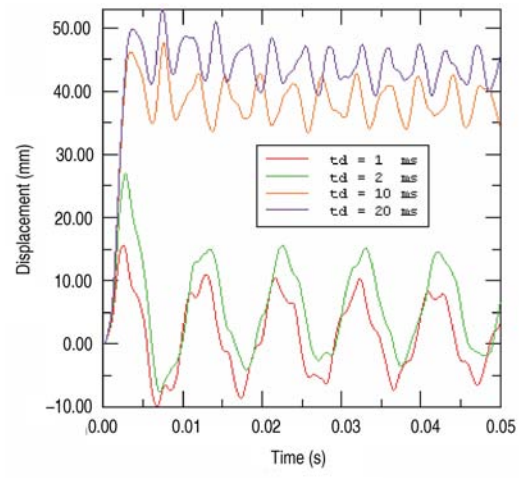

Fig. 5. Influence of loading duration for model 1

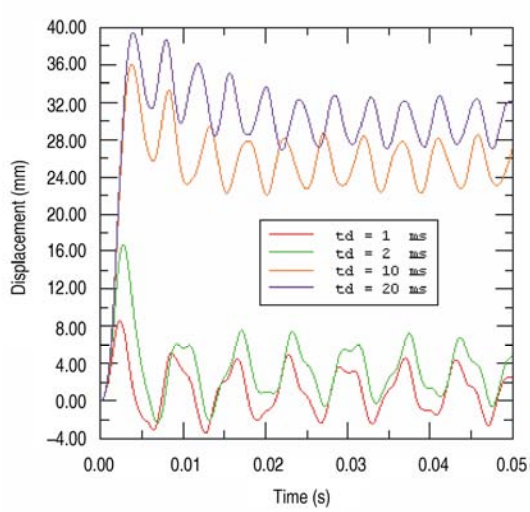

Fig. 6. Influence of loading duration for model 2

5.3. Mesh density

For model 1, 3 meshes yield the same time history for the mid-point displacement, suggesting that the results are not sensible to the mesh size (Fig. 7). However, for model 2 (Figs. 8 and 9), it can be seen that the influence of meshing can be very important for loading duration, greater than $T_n/2$ ($t_d = 20$ ms), where T_n is the fundamental period of the structure. Turkmen and Mecitoglu (1999) have found that refining the mesh leads to considerable changes in the response of stiffened plates. This difference in the behaviour between two models can be explained by the fact that the stiffeners can be subjected to almost pure bending and that using only few first order reduced integration elements through the depth of the stiffener (in this case two or three) is not sufficient to model correctly the in plane behaviour and also by the influence of the stiffeners dimensions.

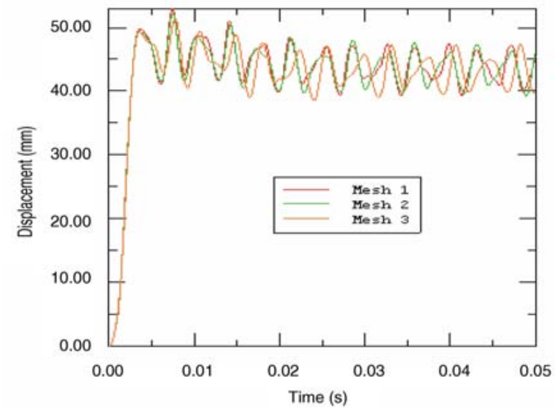

Fig. 7. Influence of meshing for model 1 (t_d = 20 ms)

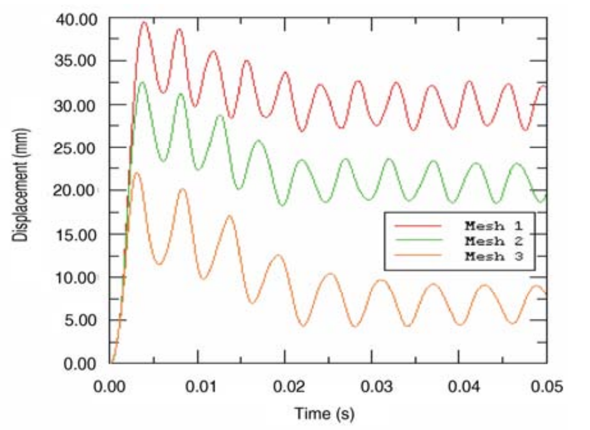

Fig. 8. Influence of meshing on model 2 (t_d = 20 ms)

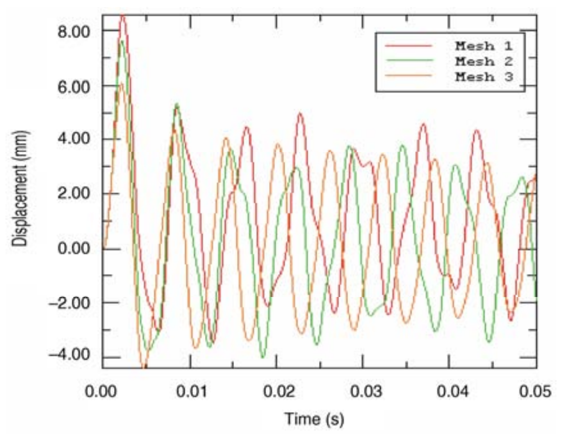

Fig. 9. Influence of meshing on model 2 (t_d = 1 ms)

5.4. Strain rate sensitivity

Strain-rate effects are included by adjusting the material dynamic yield stress at each Gauss point according to the Cowper–Symonds relation, Eq (4), (Jones 1989):

$$\sigma_y = \sigma_0 \left[1 + \left| \frac{\dot{\varepsilon}}{D} \right|^{\frac{1}{n}} \right], \qquad (4)$$

where σ_0 is the static uniaxial yield stress, σ_y is the dynamic yield stress, D and n are experimentally defined parameters. In this study the following 3 sets of values for D and n were adopted: (1) $D = 40$ s^{-1} and $n = 5$; (2) $D = 240$ s^{-1} and $n = 4.74$; (3) $D = 6844$ s^{-1} and $n = 3.91$ (Boh *et al.* 2004). When the strain-rate effect is taken into account, the yield stress increases as the strain rate. Thus, because the elastic modulus is higher than the plastic modulus, it is expected that the analysis with strain rate will be much stiffer, resulting in a decrease in the mid-point displacement. However, the rate of decrease depends on the duration of loading; for instance, for model 2 (Fig. 10), when $t_d = 20$ ms, the mid-point displacement is 39,48 mm without strain rate and 30.93 mm, when strain rate ($D = 40$ s^{-1}, $n = 5$) is included, while for $t_d = 1$ ms, the values are 8,58 mm and 7.96 mm with and without strain-rate ($D = 40$ s^{-1}, $n = 5$), respectively (Fig. 11). These results are further confirmed by the observation of the history of the plastic strain energy (Figs. 12 and 13), where it is obvious that for $t_d = 20$ ms, the plastic strain energy with strain-rate is greatly reduced compared to the case without rate indicating a stiffer response. For $t_d = 1$ ms, the difference in the plastic strain energy history for material with and without strain-rate respectively, is very small. However, consideration of different material constants (D and n) results in a very different response.

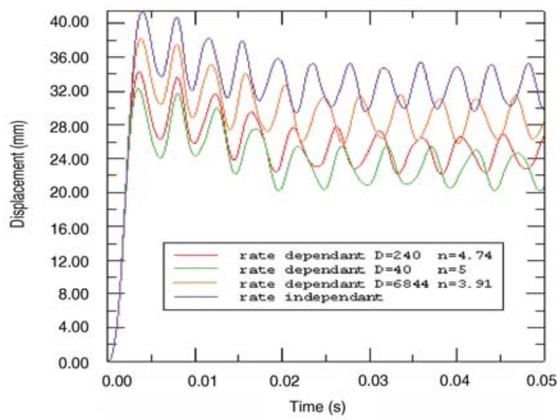

Fig. 10. Influence of strain-rate (t_d = 20 ms)

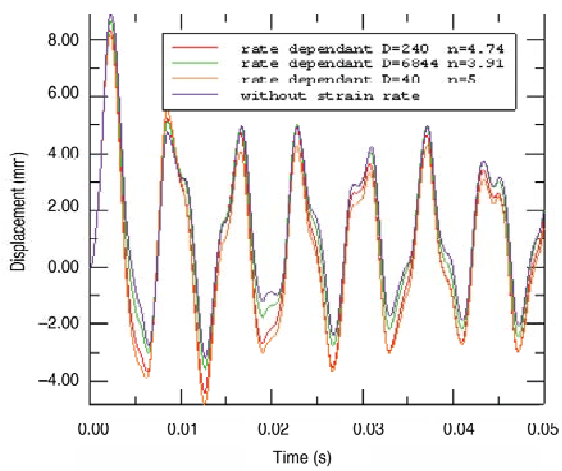

Fig. 11. Influence of strain-rate (t_d = 1 ms)

Thus, the results are sensitive to material data. Boh *et al* (2004) suggested that there are a lot of uncertainties concerning the strain-rate effects on steel structural response and there are studies on strain-rate phenomenon which are only applicable to their investigated domain and sometimes even conflicting with other studies.

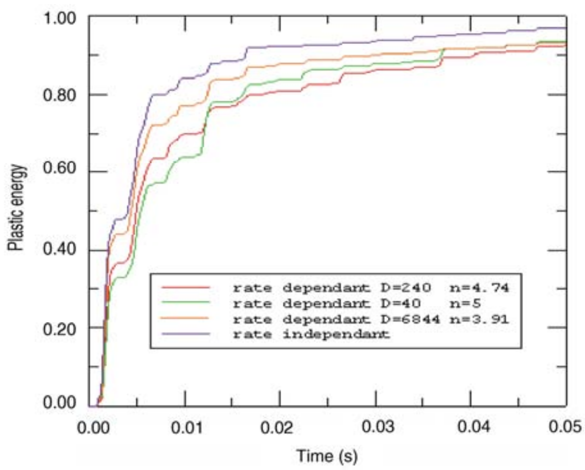

Fig. 12. History of plastic strain energy (t_d = 1 ms)

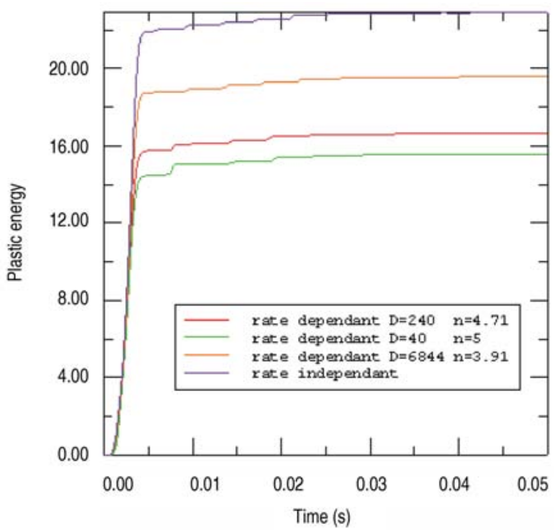

Fig. 13. History of plastic strain energy (t_d = 20 ms)

6. Conclusions

From the non-linear dynamic finite element analyses carried out to examine the behaviour of fully-fixed stiffened plates under blast loading, the following conclusions can be drawn:

- the effect of stiffener configurations can be very important, since it can affect drastically the overall behaviour of the plates as indicated by model 6,
- the time duration is one of the most important parameter since it has an influence on other parameters, such as mesh density and strain rate, and is largely dependant on the ratio $t_d/(T_n/2)$,
- mesh density is not relevant for model 1 (unstiffened plate), but for stiffened plates it can influence considerably the results especially for larger values of t_d (t_d = 20 ms),
- the inclusion of strain-rate effect results in a much stiffer response, especially for larger values of t_d resulting in lower mid-point displacement; however, results are very sensitive to the values of D and n. Thus, the strain effect should be taken into account, when analysing structures subjected to blast loading.

References

Biggs, J. M. 1964. *Introduction to structural dynamics*. London: McGraw-Hill Book Company.

Buslon, P. S. 1997. *Explosive loading of engineering structures.* London: E&FN Spon.

Boh, J. W; Louca, L. A.; Choo, Y. S. 2004: Strain rate effects on the response of stainless steel corrugated firewalls subjected to hydrocarbon explosions, *Journal of Constructional Steel Research* 60(1): 1–29.

CCM: Code de Calcul des Structures Métalliques. DTR Algérien, 1997.

Chopra, A. K. 2001. *Dynamics of structures: theory and applications to earthquake engineering*. New Jersey: Prentice Hall Inc.

Clough, R. W.; Penzien, J. 1975. *Dynamics of structures*. New York: McGraw Hill Inc.

Hibbitt, Karlsson & Sorensen. 1998. *ABAQUS/Explicit User's Manual. Version 5.8.* Pawtucket: Hibbitt, Karlsson & Sorensen, Inc.

Jacinto, A. C.; Ambrosini, R. D.; Danesi, R. F. 2001 Experimental and computational analysis of plates under air blast, *International Journal of Impact Engineering* 25(10): 927–947.

Jacob, N.; Yuen, S. C. K.; Nurick, G. N.; Bonorchis, D.; Desai A. S.; Tait, D. 2004. Scaling aspects of quadrangular plates subjected to localised blast loads experiments and predictions, *International Journal of Impact Engineering*, 30(8–9): 1179–1208.

Jones, N. 1989. *Structural impact*. Cambridge: Cambridge University Press.

Louca, L. A.; Harding, J. 1996. Response of plates to blast loading, in *Proc of International Conference on Advances in Steel Structures, Hong Kong, 11-14 December, 1996*, 677–684.

Louca, L. A.; Punjani, M.; Harding, J. E. 1996. Non-linear analysis of blast walls and stiffened to hydrocarbon explosion, *Journal of Constructional Steel Research* 37(2): 93–113.

Nurick, K. N.; Olson, M. D.; Fagnan, J. R.; Levin, A. 1995 Deformation and tearing of blast loaded stiffened square plates, *International Journal of Impact Engineering* 16(2): 273–291.

Olson, M. D. 1991. Efficient modelling of blast loaded stiffened plate and cylindrical shell structures, *Computers and Structures* 40(5): 1139–1149.

Pan, Y.; Louca, L. A. 1999. Experimental and numerical studies on the response of stiffened plates subjected to gas explosions, *Journal of Constructional Steel Research*, 52(2): 171–193.

Pan, Y. G.; Louca, L. A.; White, G. 1997. Response of stiffened plates subjected to hydrocarbon explosions, in *Proc. of the 8th International Conference on the Behaviour of Offshore Structures, Delft, Netherlands, July 7–10, 1997*, 34–45.

Rudraptana, N. S.; Vaziri, R.; Olson, M. D. 1999. Deformation and failure of blast-loaded square plates, *International Journal of Impact Engineering* 22(4): 449–467.

Schubak, R. B. 1991. *Nonlinear rigid-plastic modelling of blast loaded stiffened plates*. PhD thesis, University of British Columbia, Vancouver.

Schubak, R. B.; Anderson, D. L.; Olson, M. D. 1989a. Simplified dynamics analysis of rigid-plastic beams, *International Journal of Impact Engineering* 8(1): 27–42.

Schubak, R. B; Olson, M. D.; Anderson, D. L. 1989b. Nonlinear analysis of one-way stiffened plates under blast load, in *Proc. of the 1st International Conference "Structures under Shock and Impact"*. Ed. by P. S. Bulson. July 1989, Cambridge, MA, USA. Amsterdam: Elsevier, 345–354.

Turkmen, H. S.; Mecitoglu, Z. 1999. Dynamic response of a stiffened laminated composite plate subjected to blast load, *Journal of Sound and Vibration* 221(3): 371–389.

Xu, J.; Kirkvik, R. H. 1991. Design against explosion loads in offshore structures, in *Proc. of the 1st International Offshore and Polar Engineering Conference, Edinburgh. United Kingdom, 11–16 August, 1991*. Colorado: International Society of Offshore and Polar Engineers, 183–189.

Yuen, S. C. K.; Nurick, G. N. 2003. Experimental and numerical studies on the response of quadrangular stiffened plates. Part I: subjected to uniform blast load, *International Journal of Impact Engineering* 31(1): 55–83.

IŠSKIRSTYTĄJA SPROGIMO APKROVA VEIKIAMOS SUSTANDINTOS PLOKŠTĖS

A. Kadid

S a n t r a u k a

Atlikta išskirstytąja sprogimo apkrova veikiamų sustandintų plokščių elgsenos analizė. Šio darbo tikslas – atlikti plokščių dinaminės elgsenos analizę, esant skirtingam sąstandų išdėstymui bei įvertinant baigtinių elementų tinklo, apkrovimo trukmės ir deformacijų pokyčio jautrumo įtaką skaičiavimo rezultatams. Netiesinės judėjimo lygties skaitiniai sprendiniai gauti integruoti laiko atžvilgiu taikant baigtinių elementų ir skirtumų metodus. Itin daig dėmesio skirta viduriniojo taško įlinkių ir plastinių deformacijų energijai vertinti. Gauti skaičiavimo rezultatai parodė, kokią įtaką sąstandų išdėstymas ir anksčiau išvardyti parametrai turi išskirstytąja sprogimo apkrova veikiamų plokščių elgsenai.

Reikšminiai žodžiai: sprogimo apkrova, plokštės, sąstandos, baigtinių elementų tinklo tankumas, deformacijų pokyčio jautrumas, laiko trukmė.

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