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The Influence of Adiabatic Heat and Combined Blast Load and Fire Loading on the Response of Mild Steel Plates

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Abstract. This paper study the influence of adiabatic heat and fire loading on the behaviour of unstiffened mild steel plates subjected to close-in blast loads using finite element (FE) analysis. A quarter-symmetry 3D FE model consists of the steel plate, clamps and bolts was developed using Abaqus/CAE. Classical plasticity model was used as the material model in the steel plate and bolts. The clamps were assumed as an elastic material. Temperature-material properties relationship according to Eurocode 3 and Masui model was assigned to the steel plate. Conwep function was used to simulate the blast loads. The influence of strain rates was considered in the steel plate using the Cowper-Symonds equation. The FE model of the unstiffened plates was verified and validated against experimental data from literature, where a good agreement was achieved. The results suggest the adiabatic heat in the steel plates does not significantly influence the behaviour of the steel plates in both temperature-material properties models. The study then investigated the effect of combined blast loads and fire loading on the response of steel plates. The fire loading was applied by increasing the temperature in the steel from 200 ℃ to 1000 ℃. Excessive deformation and thinning of the plate at the central area of the plate was observed. The thinning at the central area is pronounce than the thinning of the plate at the boundary between the clamp and the steel plate. Hence, the FE analysis suggests that the failure might occur at the central area of the plate, which could suggest a tearing type of failure. This type of failure is common in plates subjected to close-in blast loads. Therefore, this study has shown that the effect of adiabatic heat is insignificant, and the combined blast-fire loading might cause a similar type of failure as in plates subjected to blast loads only.

1. Introduction

Plates subjected to close-in blast loads usually deform rapidly because of the impulsive nature of the blast pressure. With sufficient blast pressures, the plates may deform plasticly which normally caused permanent deformation. The energy from plastic deformation in deformed steel plates is converted into heat but due to the rapid deformation, the heat stays in the system. This thermodynamic process is called as adiabatic process. The adiabatic heat in the steel plates may influence the temperature in the steel plates [1]. The temperature could rise and possibly affect the dynamic response of the steel plate subjected to blast loads. Several researchers [1]–[6] have conducted analysis on the influence of adiabatic heating and temperature on steels and also other materials. Softening due to adiabatic heating depends on the strain rate [2], but it also relies on the size of the localized zone caused by different stress states [1].

Fire is another source of temperature that cause heat to generate inside the steel plate and changes its behaviour. In the last few decades, there has been a surge of interest in the effects of blast loading combined with fire loading [7]–[11]. Song and Izzuddin [10], [11] proposed a new method for the nonlinear analysis of steel frames conditions where two cases of fire and explosion loading can be applied in isolation but within the same analysis. Meanwhile, Chen and Liew [8] developed an inelastic transient approach based on a mixed fibre element to study the dynamic response of steel frame structures and I-steel subjected to blast and fire loading and obtained compatible failure modes of the structures. Ding et al. [9] introduced damage factors to evaluate the damage of rectangular steel columns under the combined loading of explosion and fire using a numerical approach.

This paper seeks to investigate the influence of both adiabatic heat and fire loading on the response of unstiffened mild steel plates subjected to close-in blast loads. A symmetry quarter model was first developed according to the input data and material properties based on the numerical model used in the research conducted by Yuen et al. [12]. Verification and validation process was then conducted using mesh sensitivity studies and comparing the displacement values with experiment data by Yuen et al. [12] respectively. Both mentioned processes obtained sufficient results that conclude that the developed model is valid to be used for an extended study. Therefore, both Masui and Eurocode 3 (EC3) as well as the inelastic heat fraction of 0.9 and specific heat of 660 J/kg °C were then added into the material properties of the temperature-dependent model. The results were analysed based on the displacement and the temperature of the plate.

2. Methodology

Figure 1 shows the experimental setup by Yuen et al. [12] in which this paper used as the main reference to numerically simulate the influence of adiabatic process and fire loading on the response of unstiffened mild steel plates subjected to close-in blast loads using finite element software (FE), Abaqus. The steel plate was tied to two steel clamps using bolts. The stand-off distance (SOD) was calculated from the centre of the surface of the target plate to the point of blast.

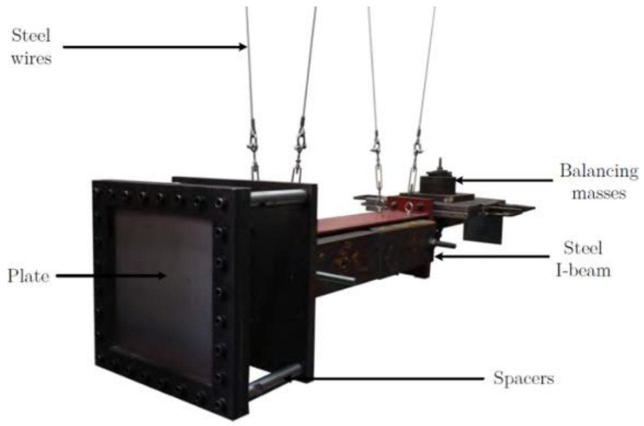

Figure 1. Experimental setup by Yuen et al. [12].

2.1. Model geometry and material properties

In this study, the FE model of the steel plate was modelled as a 3D quarter-symmetry model based on the experimental setup by Yuen et al. [12] as shown in figure 1. Figure 2 shows the numerical setup of the FE model in this study. The plate, clamps and bolts were modelled using solid elements, therefore linear eight-node brick (C3D8R) with reduced integration and hourglass control continuum elements were used for this FE model. The dimension of the quarter symmetry 3D model and the material basic properties of steel are tabulated in table 1. The size of the bolts used to secure the steel plate between the clamps was not specifically mentioned by Yuen et. al. [12]. Therefore, in this study, the size of the bolts was assumed as 14 mm. Besides, the bolts were also assumed as elastic-plastic materials with a yield strength of 640 MPa each. Meanwhile, two 20 mm thick and 50 mm width clamping frames were securing the target steel plate leaving a deformable area of 150 mm x 150 mm.

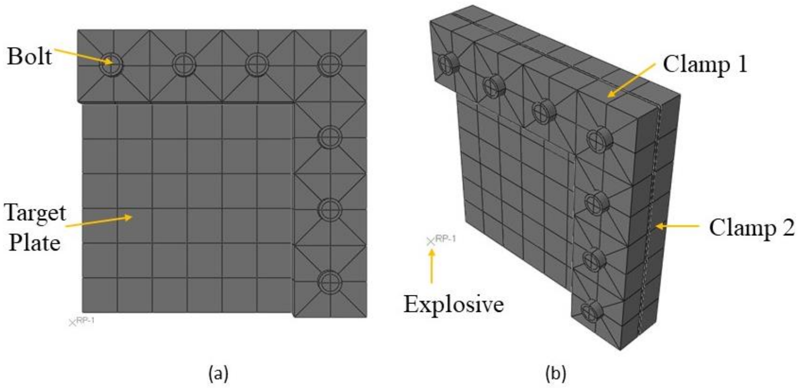

Figure 2. Simulation set-up (a) front view, (b) side view.

Table 1. Designed steel plate's details.

Size, w×h (mm)	Deformable Area, w×h (mm)	Mass Density (kg/m³)	Heat Fraction	Specific Heat (J/kg °C)
200x200	150x150	7850	0.9	660

Classical plasticity model was used as the material model in the steel plate and bolts. The clamps were assumed as an elastic material. Therefore, the yield strength is neglected. The density of the steel was taken as 7850 kg/m³. For the base model without temperature, a Young's Modulus (E) of 210000 with Poisson's Ratio of 0.3 and yield stress (σ_y) of 222 MPa were used. However, for temperature dependent model, different values of Young's Modulus (E) and yield stress (σ_y) were included into the material properties of the model based on the temperature-model of Masui [13]. Equation (1) and equation (2) [14] as reported by Masui [13] shows that both Young's Modulus, E and yield stress, σ_y are temperature dependent. Inelastic heat fraction of 0.9 was also included into the material properties of the steel plate to analyse the adiabatic effect on the response of the steel plate subjected to blast loads.

$$\begin{aligned} E &= 210 \times 10^9 - 58.34 \times 10^6\, T && for\ T \leq 600\ ℃, \\ E &= 3.1 \times 10^5 (T - 1100)^2 + 97 \times 10^9 && for\ 600\ ℃ < T \geq 1100\ ℃, \end{aligned} \tag{1}$$

$$\begin{aligned} \sigma_y &= \sigma_0 && for\ T \leq 200\ ℃, \\ \sigma_y &= \sigma_0[1 - 0.00178(T - 200)] && for\ 200\ ℃ < T < 700\ ℃, \\ \sigma_y &= \sigma_0[0.133 - (T - 700)3.884 \times 10^{-4}] && for\ 700\ ℃ \leq T \leq 1100\ ℃\,. \end{aligned} \tag{2}$$

In the Masui [13] temperature model, the specific heat was assumed as constant at 660 J/kg °C while in contrast, Eurocode 3 [15] dictates that the specific heat is influenced by the temperature. Moreover, the influence of temperature on the properties of the modulus of elasticity, proportional limit and the yield stress of the steel are considered using the reduction factor as depicted in figure 3.

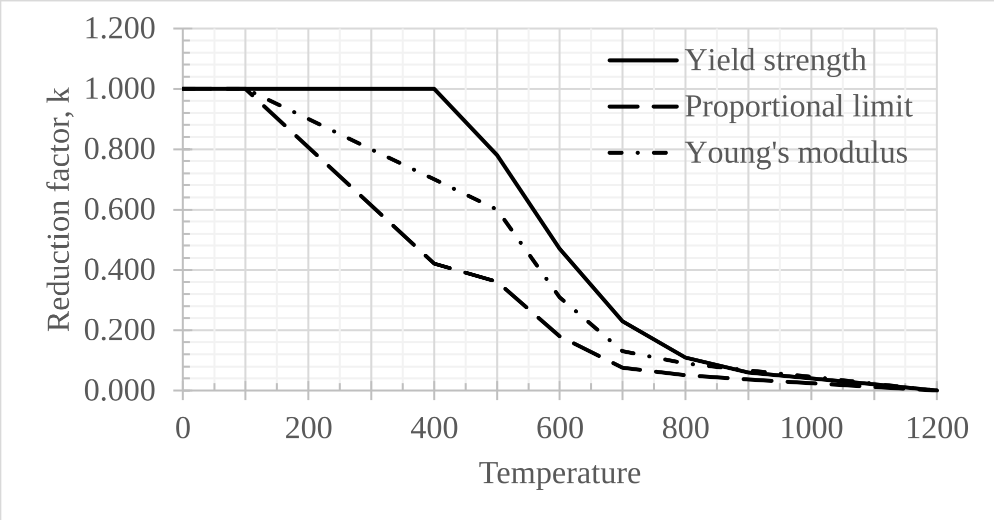

Figure 3. Reduction factors for yield strength, proportional limit, and elastic modulus according to Eurocode 3.

The mass of the plastic explosive (PE4) applied into the FE model was in the range of 8g to 28g. The blast was simulated using Conwep. Therefore, the PE4 was converted into TNT equivalent according to the empirical equation suggested by Bogosian et al. [16]. The stand-off distance (SOD) was fixed at 40 mm as shown in figure 1. The plate structure was modelled as a solid, therefore linear eight-node brick (C3D8R) with reduced integration and hourglass control continuum elements was used for this model. The clamps were restrained from translational and rotational movements. Symmetrical boundary conditions were imposed on the x-axis and y-axis simultaneously.

Surface-to- surface contact was used to model the interactions between the plate, clamps, and bolts. The plate was defined as the master surface, while the clamping frames and the bolts become the slave surface in the interaction. The pressure-over closure for normal behaviour was assigned as 'hard' contact and the friction coefficient was taken as 0.3 for contact in the tangential direction. The separation of the interacted surfaces after contact was allowed.

The influence of strain rates in the steel plate was taken into account using the Cowper-Symonds relation [6] because it is simpler thus fewer parameters were required [7] compared to the Johnson-Cook flow stress model [8]. Equation (3) shows the Cowper-Symond relation, where the coefficients D and q could vary due to various conditions [17]. In this study, the common values of D=40.4 and q=5 were used.

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$$\frac{\sigma^1 y}{\sigma_0} = 1 + \left(\frac{\dot{\varepsilon}}{D}\right)^{\frac{1}{q}} \tag{3}$$

2.2. Validation and verification

A mesh sensitivity study was conducted on the FE model, where several mesh sizes ranging from 0.5-8.0 mm were implemented into this model. The maximum displacement of the plate was the measured parameter and used to assess the sensitivity of the FE model to mesh sizes or numbers. Based on the results in table 2, the sensitivity of the FE model towards the mesh or the number of elements when the mass of explosive is constant is very small when the number of elements in the model was increased. The maximum displacement between the FE model with mesh size 1.0 mm and 0.5 mm is only differentiated by 2.54%. However, the computational time for FE model with 1.0mm mesh is shorter compared to FE model with 0.5 mm mesh where the time taken by FE model 1.0 mm is 50% faster than 0.5 mm mesh. Therefore, 1.0 mm mesh size was chosen as the most ideal size of mesh for the FE model.

Table 2. Mesh sensitivity study.

Mesh size (mm)	No. of element	Maximum displacement (mm)	Percentage Difference (%)
8.0	492	8.7	-
4.0	2536	13.7	44.64
2.0	8590	17.2	22.65
1.0	65916	19.4	12.02
0.5	520992	19.9	2.54

Eight different PE4 charges mass ranging from 8-28 g and with a fixed stand-off distance of 40 mm were used to conduct the validation assessment for this study where the measured parameter was the maximum displacement of the plate when subjected to blast loads. The results from literature [12] are compared side to side with the results obtained from the simulations as shown in table 3.

Table 3. Percent error between experimental and FE results.

Blast ID	PE4 (g)	TNT_{eqv} (g)	Maximum displacement, (mm)		Percent Error (%)
			Experiment	FE analysis	
P1	8	14.6	22.1	19.43	-12.07
P2	10	18.2	28.3	23.52	-16.88
P3	12	21.9	33.3	30.27	-9.09
P4	14	25.5	37.1	37.52	1.13
P5	16	29.1	40.0	44.40	11.00
P6	18	32.8	44.5	48.11	8.11
P7	20	36.4	Torn	52.63	-
P8	28	51.0	Torn	69.30	-

Mixed results were obtained from the validation assessment where P1-P4 values of FE analysis fall below the experimental results and P4-P6 overestimated the results. No comparison on maximum displacement was made on P7 and P8 as the plates were torn in the experiment. However, this study does not consider any damage or failure model in the FE model. Nevertheless, it can be inferred that the displacement values for both P7 and P8 are higher than P6 because of the torn on the plate. Since the displacement values for FE analysis of P7 and P8 are also much higher that experimental P6, the results are thus deemed as appropriate. From this, the developed FE model shows sufficient accuracy and thus, it can be extended for further studies as the errors are relatively low compared to other percentage error of over 20% reported in several other numerical studies of plates subjected to blast loads [18]–[20].

3. Results and discussion

The numerical investigation indicates that the deflection of the plate increases as the mass of PE4 increases. According to figure 4 and 5, 8-18 g mass of PE4 have caused low plastic deformation in the plate since vibration of the plates still presents at 0.01 second even though the plate was permanently deformed. For 20 g and 28 g mass of PE4, the plastic deformation of the plate was high and thus, caused the steel plate to have higher deflection and it can be observed that the vibration of the plates after the maximum displacement is not present.

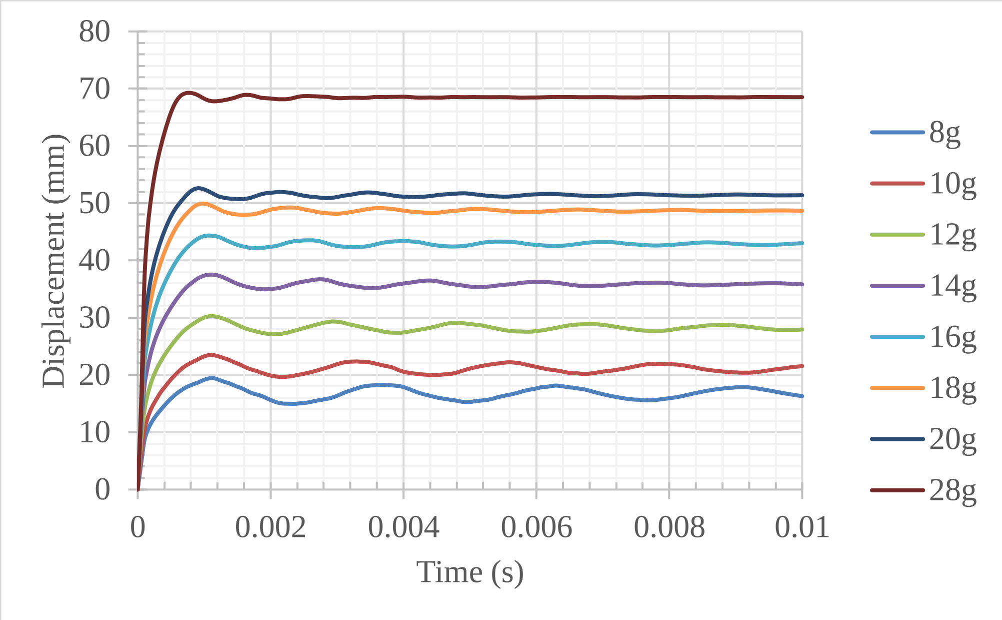

Figure 4. Displacement of steel plates with adiabatic.

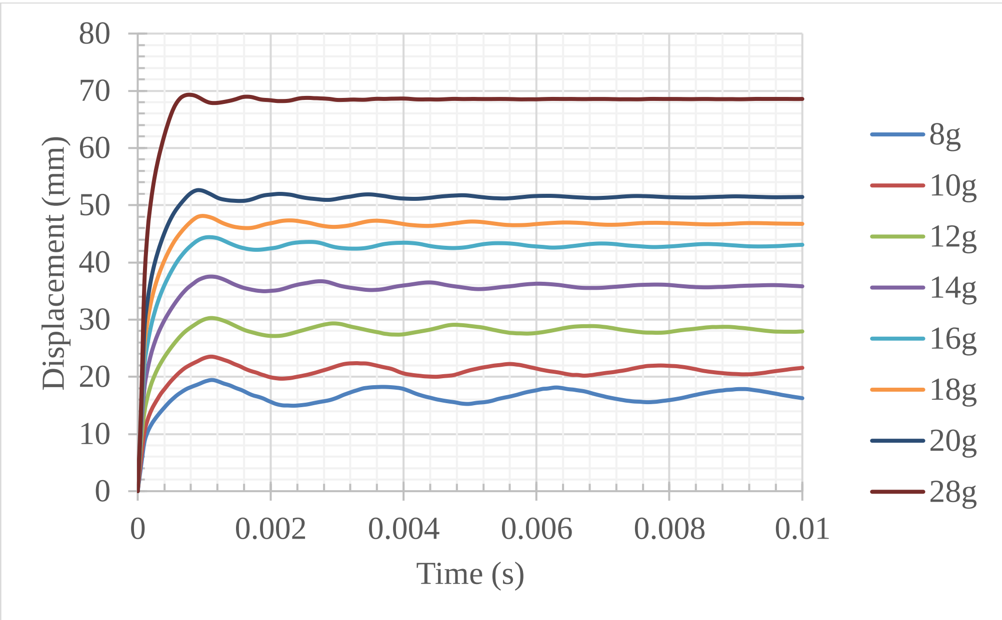

Figure 5. Displacement of steel plates without adiabatic.

Figure 6 shows the comparison of maximum displacement between the FE model with and without adiabatic process included in the analysis. The results in figure 6 suggest that the adiabatic heat generated from the deformation of the plate could be neglected. From this, it can be concluded that adiabatic does not have sufficient influence in affecting the response of mild steel plates when subjected to near-field blast loads. However, there is a difference in the temperature generated in the steel plate from the adiabatic process.

Figure 7 shows the temperature of the steel plates predicted using FE analysis using two different temperature-dependant material models, which were EC3 and Masui model. The results revealed the EC3 model predicted higher heat compared to the Masui model. The difference is more significant when the plates experienced higher displacement. The EC3 predicted higher heat could be contributed by the fact that the specific heat in Eurocode 3 is influenced by temperature rather than constant, as assumed in the Masui model. Nevertheless, both temperature dependent models give results of temperature way below the threshold that allow it to influence the steel strength and their behaviour. Hence, it could postulate that the blast pressure in this study did not generate enough energy that can be converted into heat and temperature that will affect the behaviour of the mild steel plates.

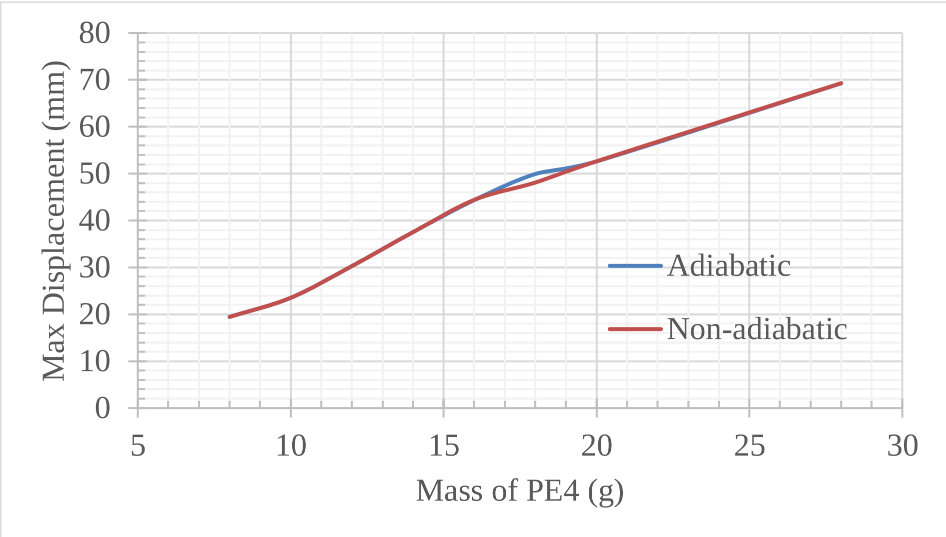

Figure 6. Difference of maximum displacements with and without adiabatic effect.

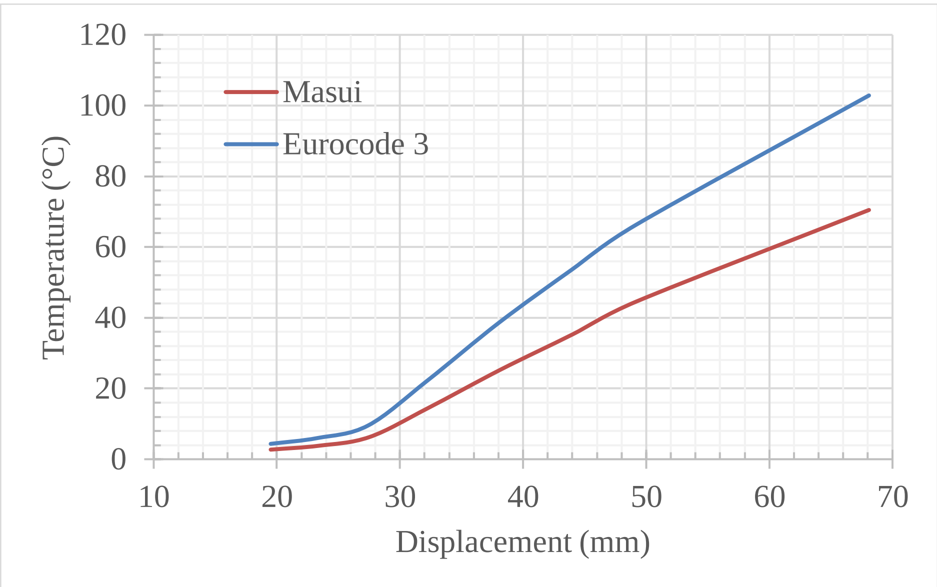

Figure 7. Difference of temperature generated using Masui and EC3.

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In this study, the influence of combined blast and fire loads on the response of steel plates when subjected to close-in blast loads was investigated using the material model as in Masui et al. [13]. For this study, the steel plates were subjected to three different PE4 masses, which were 8 g, 16 g and 28 g. The study was conducted in two-time steps were in the first-time step, the fire loading was simulated by applying a constant temperature where for each case starting from 200 °C until 1000 °C with an increasing magnitude of 200 °C. In the second-time step, the blast load was applied to the heated steel plates. In general, the plate displacement increases as the fire and blast loads increase as shown in figure 8. The steel plate experienced excessive deformation especially when subjected to 16 g and 28 g of PE4 where the plate displaced more than 1000 mm from their origin when the temperature is beyond 600 °C as shown in inset of figure 8.

Moreover, the modelling indicates that the deformation of the plate could possibly lead to thinning of the plate at the central area and boundary of the steel plates when the temperature reached beyond 600 °C as presented in figures 9-11. The thinning might indicate possible failure location in the steel plate as the equivalent plastic strains predicted from the simulations, as tabulated in table 4, exceeded 0.3, which could be considered common fracture strain for mild steel plates [21]. Figure 9-11 indicates the strain localisation and thinning of the steel plates happens at the centre of the plate, where the blast pressure is the highest, and the edge of clamp support (below clamp area). Based on this observation, the plate might fail due to tearing at the centre and the support of the plate. The plate might tear first at the centre area and followed by at the support area, which is almost a similar type of failure observed in steel plates subjected to blast loads only [14], [22].

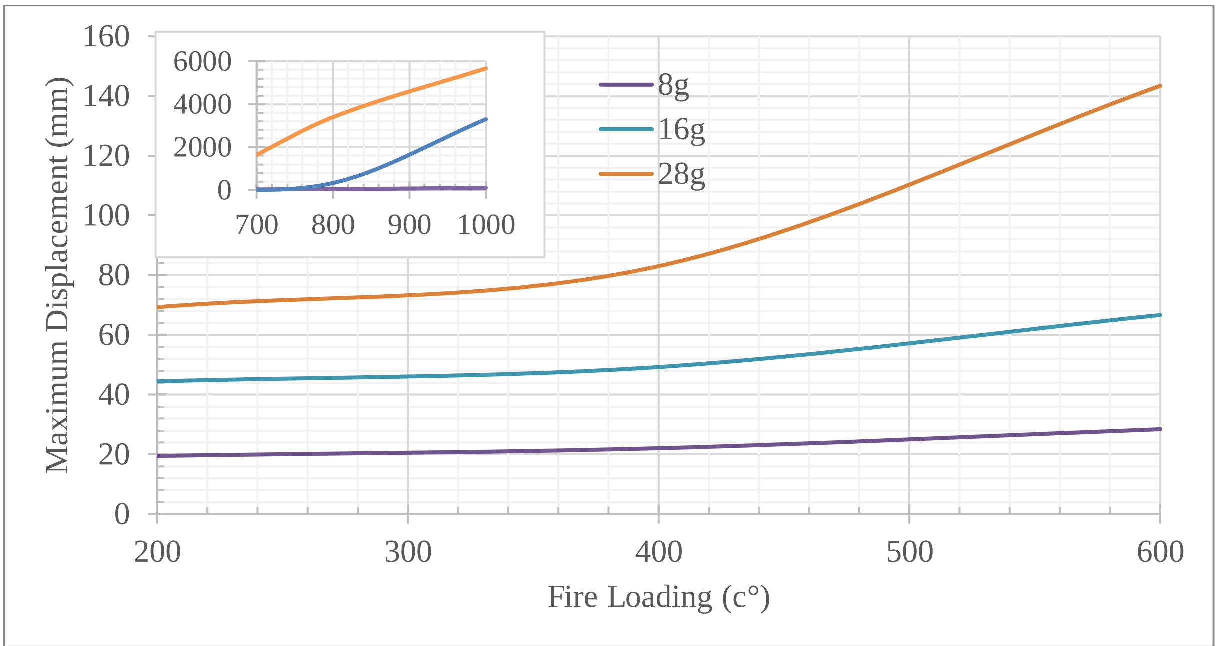

Figure 8. Maximum displacement of fire loading.

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Table 4. Maximum equivalent plastic strain in steel plates.

	Equivalent Plastic Strain (PEEQ)		
Temperature (°C) / PE4 mass (g)	8	16	28
200	0.050	0.250	0.440
400	0.075	0.320	0.580
600	0.100	0.500	43.550
800	0.230	380.00	521.00
1000	1.010	898.00	969.00

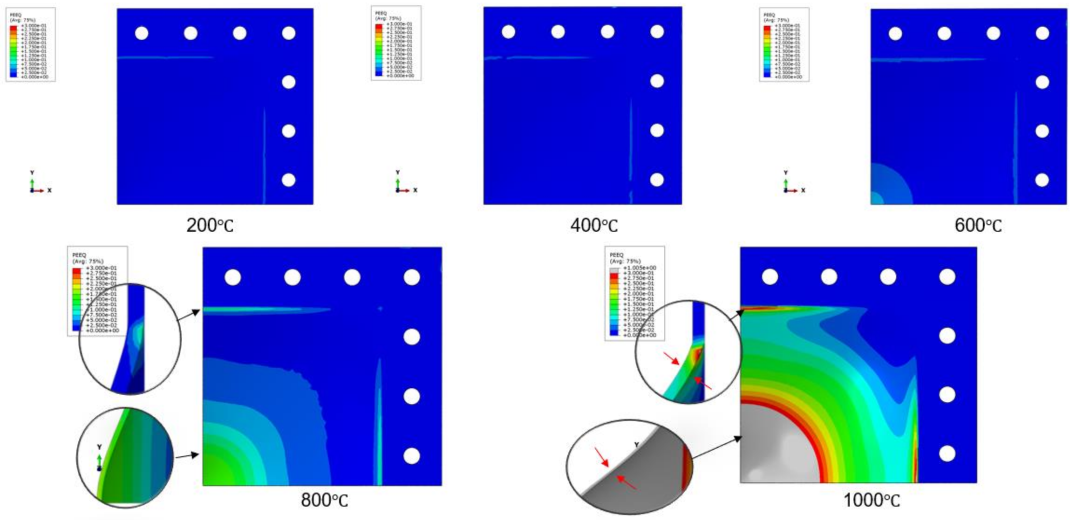

Figure 9. Strain of 8 g mass steel plate.

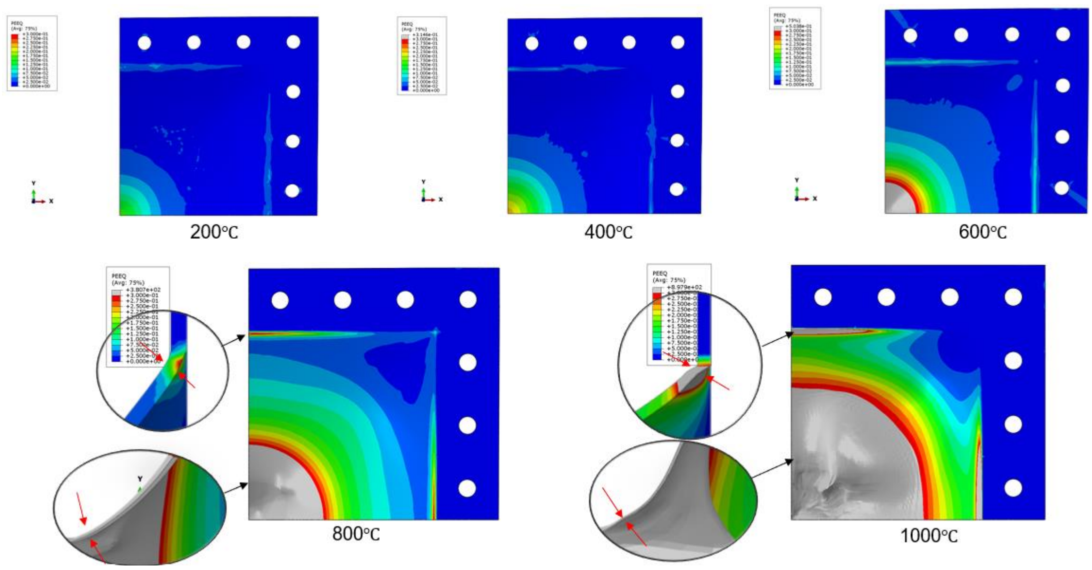

Figure 10. Strain of 16 g mass steel plate.

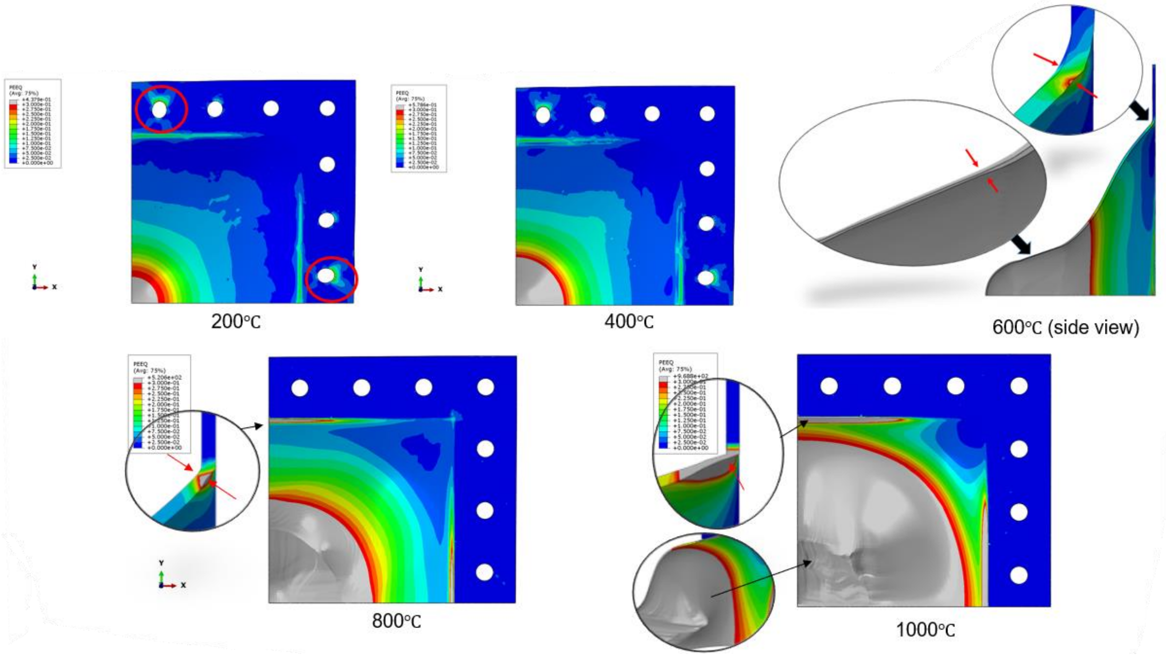

Figure 11. Strain of 28 g mass steel plate.

4. Conclusion

This study presents a numerical investigation to assess the influence of adiabatic process and fire loading on the response of unstiffened mild steel plate subjected to close-in blast loads. The FE model was developed using the data obtained from Yuen et al. [12] and the verified and validated accordingly. The study was then extended by applying Masui and EC3 equation models into the material properties of the temperature-dependent model for adiabatic effect and then inelastic heat fraction of 0.9 and specific heat of 660 J/kg °C as well as fire loading ranging from 200 °C to 1000 °C.

The influence of adiabatic heat on the response of steel plate models exhibits insignificant difference in terms of the maximum displacement of the steel plate. The effect is almost negligible and thus could be ignored for the range of PE4 masses and SOD. The study also has shown that the temperatures obtained from both Masui and EC3 are way below the threshold that can influence the strength of the steel. Therefore, the adiabatic effect could not influence the deflection of the mild steel plates when subjected to close-in blast loads.

Finally, a higher possibility of failure when subjected to fire loading was seen at mass of PE4 16 g and 28 g when the temperature is at 800 °C and above compared to 8 g. Furthermore, the failure was predicted to occur at the detonation point and at the edge of clamp support. This predicted type of failure is similar to steel plates subjected to blast loads only.

5. References

[1] S. Klitschke, A. Trondl, F. Huberth, and M. Liewald, “Adiabatic heating under various loading situations and strain rates for advanced high-strength steels,” *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 418, no. 1, 2018, doi: 10.1088/1757-899X/418/1/012123.

[2] J. Rämö, V. T. Kuokkala, and T. Vuoristo, “Influence of strain rate and adiabatic heating on the deformation behavior of cold heading steels,” *J. Mater. Process. Technol.*, vol. 209, no. 11, pp. 5186–5194, 2009, doi: 10.1016/j.jmatprotec.2009.03.004.

[3] M. Nasraoui, P. Forquin, L. Siad, and A. Rusinek, “Influence of strain rate, temperature and adiabatic heating on the mechanical behaviour of poly-methyl-methacrylate: Experimental and modelling analyses,” *Mater. Des.*, vol. 37, pp. 500–509, 2012, doi: 10.1016/j.matdes.2011.11.032.

[4] B. Jia, P. Chen, A. Rusinek, and Q. Zhou, “Thermo-viscoplastic behavior of DP800 steel at quasi-static, intermediate, high and ultra-high strain rates,” *Int. J. Mech. Sci.*, vol. 226, no. May, p. 107408, 2022, doi: 10.1016/j.ijmecsci.2022.107408.

[5] E. Cadoni and D. Forni, “Mechanical behaviour of a very-high strength steel (S960QL) under extreme conditions of high strain rates and elevated temperatures,” *Fire Saf. J.*, vol. 109, no. July, p. 102869, 2019, doi: 10.1016/j.firesaf.2019.102869.

[6] C. Defence and H. Security, “The formation of a blast wave by a very intense explosion. - II. The atomic explosion of 1945,” *Proc. R. Soc. London. Ser. A. Math. Phys. Sci.*, vol. 201, no. 1065, pp. 175–186, 1950, doi: 10.1098/rspa.1950.0050.

[7] Y. Sun *et al.*, “Damage effect of steel circular tube subjected to fire and blast,” *J. Constr. Steel Res.*, vol. 176, p. 106389, 2021, doi: 10.1016/j.jcsr.2020.106389.

[8] H. Chen and J. Y. R. Liew, “Explosion and Fire Analysis of Steel Frames,” no. July, pp. 687–692, 2002, doi: 10.1142/9789812776228_0101.

[9] Y. Ding, M. Wang, Z. X. Li, and H. Hao, “Damage evaluation of the steel tubular column subjected to explosion and post-explosion fire condition,” *Eng. Struct.*, vol. 55, pp. 44–55, 2013, doi: 10.1016/j.engstruct.2012.01.013.

[10] B. A. Izzuddin, L. Song, A. S. Elnashai, and P. J. Dowling, “An integrated adaptive environment for fire and explosion analysis of steel frames - Part II : verification and application,” *J. Constr. Steel Res.*, vol. 53, no. 1, pp. 87–111, 2000.

[11] L. Song, B. A. Izzuddin, A. S. Elnashai, and P. J. Dowling, “An integrated adaptive environment for fire and explosion analysis of steel frames - Part I:: Analytical models,” *J. Constr. Steel Res.*, vol. 53, no. 1, pp. 63–85, 2000, doi: 10.1016/S0143-974X(99)00040-1.

[12] S. Chung Kim Yuen, A. Butler, H. Bornstein, and A. Cholet, “The influence of orientation of blast loading on quadrangular plates,” *Thin-Walled Struct.*, vol. 131, no. April, pp. 827–837, 2018, doi: 10.1016/j.tws.2018.08.004.

[13] “Shape Correction of Steel Strip by Tension Leveller*,” vol. 17, pp. 475–484, 1977.

[14] S. C. K. Yuen and G. N. Nurick, “Experimental and numerical studies on the response of quadrangular stiffened plates. Part I: Subjected to uniform blast load,” *Int. J. Impact Eng.*, vol. 31, no. 1, pp. 55–83, 2005, doi: 10.1016/j.ijimpeng.2003.09.048.

[15] B. S. En, “Eurocode 3 : Design of steel structures —,” 2005.

[16] D. Bogosian, M. Yokota, and S. Rigby, “TNT equivalence of C-4 and PE4: A review of traditional sources and recent data,” *24th Int. Symp. Mil. Asp. Blast Shock (MABS 24)*, no. September, pp. 1–15, 2016.

[17] N. S. A. Razak, A. Alias, N. M. Mohsan, and S. A. Masjuki, “The Influence of Cowper-Symonds Coefficients on the Response of Stiffened Steel Plates Subjected to Close-In Blast Loads,” *Key Eng. Mater.*, vol. 912 KEM, no. March, pp. 171–184, 2022, doi: 10.4028/p-ha2dxu.

[18] L. Gan, Z. Zong, J. Lin, Y. Chen, M. Xia, and L. Chen, “Influence of U-shaped stiffeners on the blast-resistance performance of steel plates,” *J. Constr. Steel Res.*, vol. 188, no. December, 2022, doi: 10.1016/j.jcsr.2021.107046.

[19] A. Markose and C. L. Rao, “Failure Analysis of V-shaped Plates under Blast Loading,” *Procedia Eng.*, vol. 173, pp. 519–525, 2017, doi: 10.1016/j.proeng.2016.12.080.
[20] N. Mehreganian, L. A. Louca, G. S. Langdon, R. J. Curry, and N. Abdul-Karim, “The response of mild steel and armour steel plates to localised air-blast loading-comparison of numerical modelling techniques,” *Int. J. Impact Eng.*, vol. 115, no. May 2017, pp. 81–93, 2018, doi: 10.1016/j.ijimpeng.2018.01.010.
[21] J. Fagnan, “Failure analysis of stiffened and unstiffened mild steel plates subjected to blast loading.,” 1996.
[22] G. S. Langdon, S. C. K. Yuen, and G. N. Nurick, “Experimental and numerical studies on the response of quadrangular stiffened plates. Part II: Localised blast loading,” *Int. J. Impact Eng.*, vol. 31, no. 1, pp. 85–111, 2005, doi: 10.1016/j.ijimpeng.2003.09.050.

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