BLAST RESISTANCE OF CRACKED STEEL STRUCTURES REPAIRED WITH CFRP COMPOSITE PATCH

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ABSTRACT

In this paper the blast resistance of cracked steel structures repaired with fibre-reinforced polymer (FRP) composite patch are investigated. The switch box which has been subjected to blast loading is chosen for a detailed study. For impulsively loaded structures, the structural damage and response depends on the impulse rather than the pressure pulse. In this regard, the blast wave is modelled as a uniform rectangular pressure pulse distributed over the sides of the switch box. The blast behaviour of a simple steel box is modelled using LS-DYNA software. The steel material is modelled using isotropic hardening model, pertaining to Von Mises yield condition with isotropic strain hardening, and strain rate-dependent dynamic yield stress based on the Cowper and Symonds model. Three different cracked structures are chosen to investigate their capability in dissipating the blast loading. To improve the blast resistance, the cracked steel structures are stiffened using carbon fibre-reinforced polymer (CFRP) composite patches. The repaired patches reduce the stress field around the crack as the stress is transferred from the cracked zone to them. This situation prevents the crack from growing and extends the service life of the steel structure. It will be shown that CFRP repairing can significantly increase the blast resistance of cracked steel structures.

1. INTRODUCTION

The susceptibility of civilian buildings when exposed to explosions has been shown by the latest terrorist attacks or industrial accidents. A blast wave from explosion acting directly in a building can cause major economic and human losses. As result, the number of studies in the structural response, retrofitting and repairing of structures has increased in the last years. As experimental full-scale test are quite expensive, the need of numerical analysis took a very important role in the development of knowledge in this field.

In this paper the blast resistance of cracked steel structures repaired with carbon fibre-reinforced polymer (CFRP) composite patch are investigated. Three different cracked structures are chosen to investigate their capability in dissipating the blast loading. Experimental studies with HE (High Explosive) were conducted in steel switch boxes. The peak side-on overpressure ranged from 100 kPa to 800 kPa and the reflected pressure (pressure experienced in the side of the box that faced the charge) ranged from 320 kPa to 4 MPa. The duration of the positive phase of the blast wave was around 8 ms for the highest peak side-on overpressure and 17 ms for the lower one [1] .

Previous studies have shown several different solutions to predict the structure response to blast loading. These studies lead to satisfactory results in the prediction of the permanent deformations of structures subjected to blast loading using SDOF (Single Degree of Freedom) models [2]-[6]. This approach has however several limitations. With the increase of computers capacity and the constant development of software, FE (Finite Elements) method has been getting the attention of the scientific community in the past few years. Three major numerical codes, Abaqus [7], Ls-Dyna [8] and Autodyn [9] have been used to model structures and structural elements subjected to blast loading. Yuen *et al* [10],[11] studied the response of quadrangular stiffened plates subjected to uniform blast loading. They have also investigated [12] the deformation of mild steel plates subjected to large-scale explosions. According to their results the use of the Hopkinson-Cranz scaling laws have proven to be useful to evaluate pressures, time durations and impulses; and the use of proper explicit dynamic codes can lead to a reasonable agreement with experimental results.

Jama *et. al*. [13] through numerical modelling studied square tubular steel beams subjected to transverse blast loading using LS-DYNA and concluded that these elements undergo local cross-sectional deformation followed by global beam bending deformation and highlighted the importance of the strain-rate hardening for proper detail in both local and global deformation. Nurick *et al* [14]-[16] studied the influence of boundary conditions of the loading of rectangular plates subjected to localized blast loading. They showed that axial crushing of tubes sandwiched between steel panels could be used to absorb significant energy from a blast load and studied the post-failure motion of steel plates subjected to blast loading. Sabuwala *et. al.* [17] analysed beam to column connections subjected to blast loads, showing that the TM5-1300 over-designs these elements. Krauthammer [18] proposed a model to predict the behaviour of structural concrete and structural steel connections subjected to blast loading conducting a series of numerical simulations and concluded that the current design procedures should be modified for a better prediction under these loading conditions. Børvic *et. al*. [19], [20] managed to predict the structural response of a protective structure subjected to blast loading using LS-DYNA achieving a good relation with the deformations verified in the experimental studies. Hanssen *et. al*. [21] investigated the behaviour of aluminium foam panels subjected to blast loading, and both the analytical and the non-linear finite element analysis shared the same conclusions.

In this work Finite Element (FE) software Ls-Dyna was used to model a blast loading problem. This software allows three different approaches: (i) Pure Lagrangian formulation, the load is idealised as a pressure-time curve applied directly to the surface; (ii) Running an Eulerian simulation before the Lagrangian simulation, the objective is to obtain the pressure-time load on all faces around the structure; (iii) The Eulerian formulation can be applied with the Lagrangian formulation to have a full coupling between the blast waves and the structure deformations, the use of the coupled Eulerian-Lagrangian formulation increases considerably the computational time.

Børvic *et. al*. [22] compared the response given using the coupled formulation and the pure Lagrangian formulation. The results showed a good agreement between these two approaches when using commercial software [23] or expressions in the literature [24]-[26] to obtain the pressure-time profile of the blast load. To model loading conditions on the switch boxes the pressure-time recorded in the experimental studies was applied to the structure using a pure Lagrangian formulation. The steel material is modelled using isotropic hardening model, pertaining to Von Mises yield condition with isotropic strain hardening, and strain rate-dependent dynamic yield stress based on Cowper and Symonds model. To improve the blast resistance, the cracked steel structures are stiffened using FRP composite patches. The capacity of the FRP to improve the structure response to blast loading has taken the attention of the scientific community, with several studies performed both experimental and numerical in RC structures [27]-[31] and masonry structures [32]-[37]. Most of previous researches have shown that the FRP has improved significantly the structural response of this kind of structures subjected to blast loading.

The aim of this work is to show the CFRP as a valid solution for the repairing of steel structures, reducing the stress field around the crack as the stress is transferred from the cracked zone to the FRP. This situation prevents the crack from growing and extends the service life of the steel structure. By comparison with the experimental results this work intends to provide guide lines for the modelling of this type of structures regarding blast loading.

2. EXPERIMENTAL STUDY

A number of switch boxes were exposed to blast overpressure from HE in a number of tests. These boxes were carbon steel boxes. In each test, boxes were placed at locations to receive specific overpressure loading for the explosive charge used. Figure 1 shows a typical general arrangement. It can be seen that for each test, one box had the front face facing the charge and another had its side face facing the charge.

Peak side-on overpressures in tests was ranged from 100 kPa to 800 kPa. The reflected pressure (pressure experienced by the side of the box that faced the charge) ranged from 320 kPa to 4 MPa. The duration of the highest peak side-on overpressure was around 8 ms and lower ones around 17 ms for the positive phase of the blast wave. These are within the range of pressure durations that are to be expected in detonations.

Figure 1 – General scheme of the experimental study [1].

One of the characteristics of these HE tests is that pressure decayed rapidly at these levels of overpressure. Thus, the peak side-on pressure on the face closer to the charge is larger than another face at the back. It is noted that in some cases the back face was pushed outwards (rather than crushed inwards). This is due to the effect of adiabatic compression. The crushing of the front face caused an increase in internal pressure which deformed the back face outwards. After the test, the subjects were measured in terms of residual deformation and the results recorded. No significant deformation occurred until peak side-on overpressure exceeded 470 kPa (reflected pressure of 2.7 MPa) on the side facing the blast [1]. For the purpose of the following work the T3 test will be used. In this test the reflected pressure, P_r, was 2.39 MPa, the incident pressure, P_i, was 0.53 MPa and the positive phase duration, t_d, was 11.58 ms.

3. FINITE ELEMENT MODELLING (FEM)

To model the switch boxes the pressure-time recorded in the experimental studies was applied to the structure and used a pure Lagrangian formulation for the explicit simulation. The box was modelled with thin-shell elements specific for explicit dynamic analysis, with a thickness of 1.5 mm; the dimensions are presented in Figure 3a. The steel was modelled using isotropic hardening model and for the material properties several previous researches were studied and according to the expected strain rate for this kind of action and observing the work presented in [13], the mechanical properties applied to the material model are shown in Figure 3b.

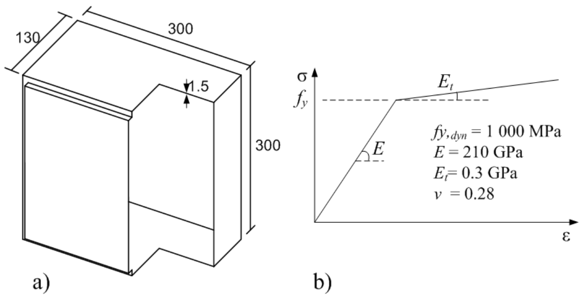

Figure 3 – a) Scheme of the switch box and b) Bilinear isotropic material model of steel (All dimensions in mm).

The applied load was modelled as a pressure time curve with a triangular shape as shown in Figure 4. In the side facing the blast the reflected pressure was applied and also in all other faces the incident pressure was applied. In all cases the pressure was applied inwards.

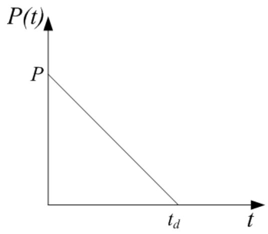

Figure 4 – Triangular shaped load applied in the models.

3.1. FEM of Simple steel box

The first step of this study was to properly calibrate a geometric and material model. This was possible by comparison of the simple tested boxes with the simple model. In this simple model the normal switch box is modelled and the T3 loading data is applied.

As shown in Figure 5 the deformed shape of the experimentally tested box and the modelled box are identical. The residual maximum deformation in the side face of the test subject is 55 mm and the residual maximum deformation in the side face of the modelled box is 53.90 mm. This represents a difference of 2%.

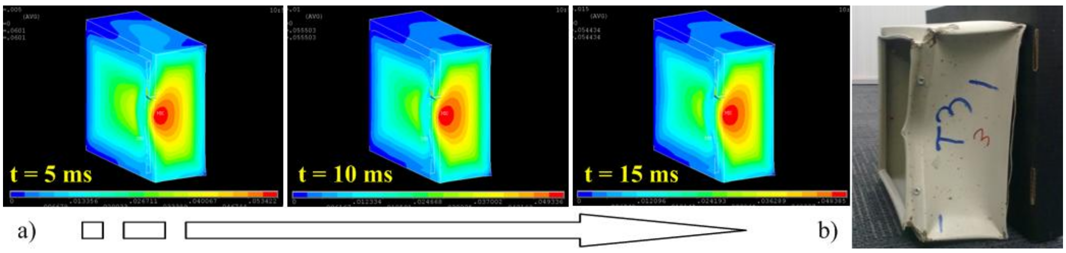

Figure 5 - Comparison of the FE model with the relevant experimentally tested box.

3.2. FEM of cracked steel box

The objective of this part of the study was to model the box with a “crack” on the side facing the blast. At this stage the influence of the crack orientation was studied, three different orientations were taken into consideration. Cracks are 20 mm long and the centre of the crack is coincident with the centre of the side face of the switch box. The mesh around the crack was taken into special consideration and it was refined in its edges as shown in Figure 6.

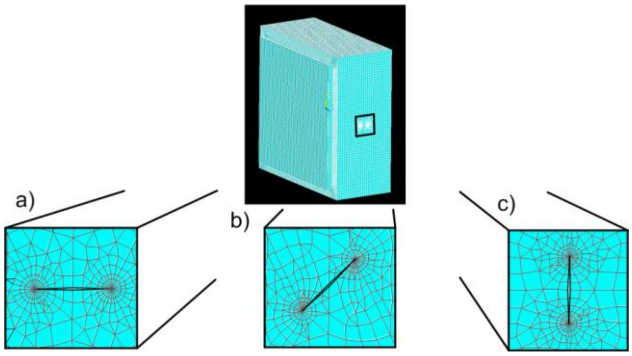

Figure 6 - Detailed mesh around the crack for the three models: a) crack at 0 degrees; b) crack at 45 degrees; c) crack at 90 degrees.

In Figure 7 various stages of the deformed shape during the analysis are shown for the model with the crack at 0 degrees.

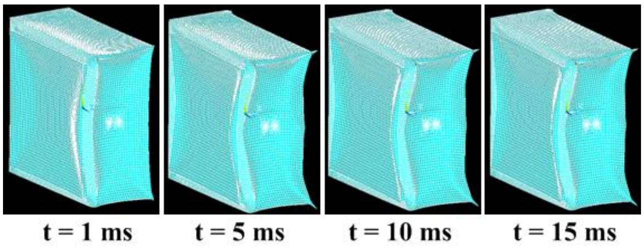

Figure 7 - Various stages of element deformation for a steel box with a crack (0˚) in the middle.

Displacement distribution of the principal load direction for different time steps is presented in Figure 8a. The node with the most deformation has the displacement history presented in Figure 8b.

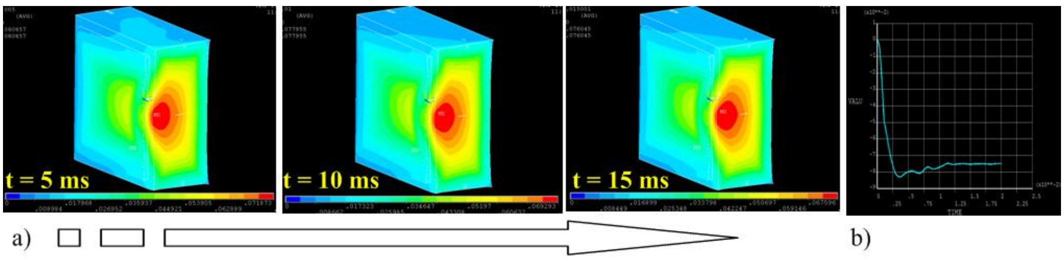

Figure 8 – a) Various stages of displacement distribution for a steel box with a crack (0˚) in the middle and b) obtained displacement-time diagram.

The comparisons between residual deformations of simple box with three cracked boxes are in Table 1. As it is shown there is no significant difference derived from the crack orientation and both three crack models present themselves with an increase of around 39% in the residual deformation when compared with the un-crack model.

Table 1 – Summarised results for the cracked models.

Model	*Crack Length (mm)*	*Crack Orientation (degrees)*	*Residual deformation (mm)*
T3	-	-	53.90
CR1_20_0	20	0	75.34
CR1_20_45	20	45	74.67
CR1_20_90	20	90	74.27

The behaviour in time of all four models presented above can be seen in Figure 9. As the behaviour are similar, for the rest of this work only the cracked model at 0 degrees is considered.

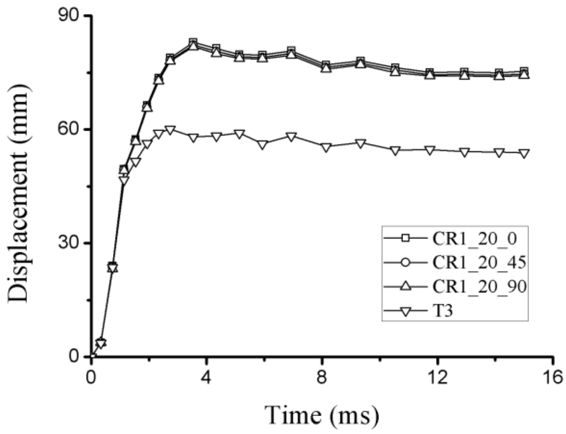

Figure 9 – Deformation in time for the simple model and three cracked models.

3.3. FEM of repaired cracked steel box

To repair the structure, the cracked steel structures are stiffened using CFRP composite patches. The capacity of the FRP to improve the structure response to blast loading has taken the attention of the scientific community, with all the previous research showing that the FRP can be a good choice when dealing with stiffness necessities.

In this particular work the objective was to repair the cracked structure with CFRP patches and evaluate the improvement of this repair. The influence of several aspects regarding the CFRP patch was also studied, by using several different models to study the influence of the patch thickness, the patch size and the orientation of the patch fibres. The CFRP patch was modelled with a layered thin-shell element type specific for explicit dynamic analysis and applied on top of the cracked zone as shown in Figure 10. The contact between the FRP patch and box was modelled using a *nodes impacting surface* with a friction coefficient of 0.30 which was measured experimentally to avoid lateral movements. The CFRP patches were modelled based on Chang-Chang failure criterion applied in composite damage model.

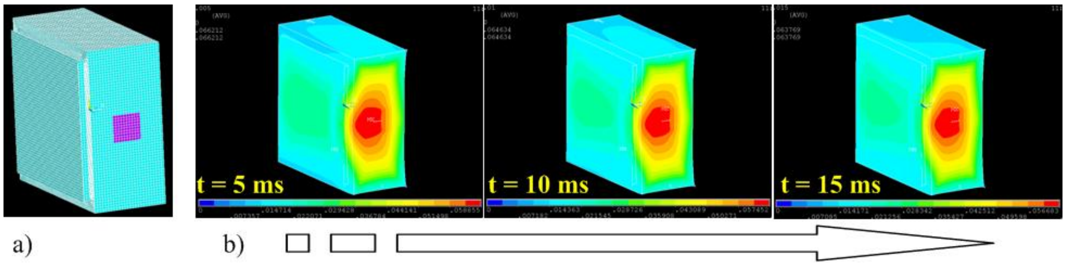

Figure 10 – a) FEM of repaired cracked box with CFRP patch and b) various stages of FE simulations.

3.3.1. Effect of the patch thickness

In this part the effect of patch thickness on the blast resistance of cracked box is investigated. With the same position as before the CFRP patch with three different thicknesses of 1.5, 2.0 and 2.5 mm were modelled. The results are summarised in table 2. As shown in the next table, there are no significant differences when varying the patch thickness when applied in this situation.

Table 2 – Effect of CFRP patch thickness on the residual deformation.

Model	*Patch thickness (mm)*	*Number of layers*	*Patch size (mm)*	*Lay-ups*	*Residual deformation (mm)*
CR_1.5_40_0	1.5	3	40	$[0]_3$	66.08
CR_2_40_0	2.0	4	40	$[0]_4$	66.80
CR_2.5_40_0	2.5	5	40	$[0]_5$	66.97

3.3.2. Effect of the patch size

To verify the influence of the patch size in the residual deformation of the box five different sizes, all square, and all with the same thickness and fibre orientation were investigated. The results are presented in Table 3.

Table 3 – Effect of FRP patch size on the residual deformation.

Model	*Patch thickness (mm)*	*number of layers*	*Patch size (mm)*	*Lay-ups*	*Residual deformation (mm)*
CR_2_40_0	2.0	4	40	$[0]_4$	66.80
CR_2_50_0	2.0	4	50	$[0]_4$	63.76
CR_2_70_0	2.0	4	70	$[0]_4$	58.63
CR_2_80_0	2.0	4	80	$[0]_4$	65.61
CR_2_90_0	2.0	4	90	$[0]_4$	84.47

Figure 11 represents the relation between the maximum residual deformation on the box side facing the blast and the size of the FRP repair patch.

It is important to realise that the behaviour of the system differs from size to size, as shown in Figure 12. As can be seen, the variation of patch size has no significant effect on the blast resistance of cracked steel structures. However, deformations are variable during the blast period. For example for small patch sizes (*e.g.* 40×40 mm^2) the deformation increases sharply in comparison with the deformation of patch size of 90×90 mm^2.

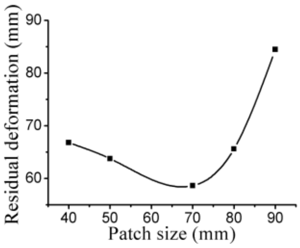

Figure 11 – Comparison of residual deformation vs Patch size in cracked box repaired with FRP patches.

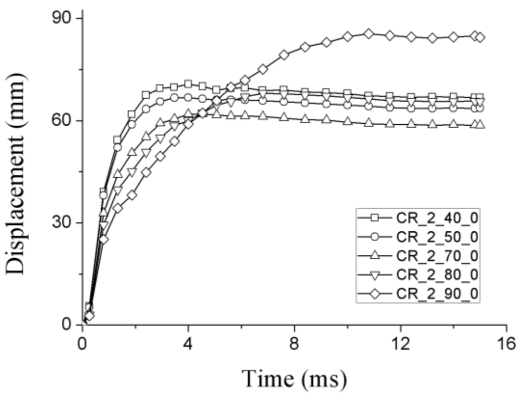

Figure 12 – Deformation in time for all modelled sizes of FRP patch.

3.3.3. Effect of the laminate design

The final aspect was the influence of the orientation of the fibres in each layer of the CFPR patch. Three types of arrangements were chosen for the related thickness: a) $[0]_n$, b) $[90]_n$, c) $[0/90]_n$, d) $[0/90/0]_n$ and $[0/90/0/90/0]_n$.

Table 4 – Effect of laminate design on the residual deformation.

Model	*Patch thickness (mm)*	*Number of layers*	*Patch size (mm)*	*Lay-ups*	*Residual deformation (mm)*
CR_1.5_40_0	1.5	3	40	$[0]_3$	66.08
CR_1.5_40_90	1.5	3	40	$[90]_3$	66.50
CR_1.5_40_090	1.5	3	40	[0/90/0]	66.33
CR_2_40_0	2.0	4	40	$[0]_4$	66.80
CR_2_40_90	2.0	4	40	$[90]_4$	66.71
CR_2_40_090	2.0	4	40	$[0/90]_2$	66.59
CR_2.5_40_0	2.5	5	40	$[0]_5$	66.97
CR_2.5_40_90	2.5	5	40	$[90]_5$	67.14
CR_2.5_40_090	2.5	5	40	[0/90/0/90/0]	66.99

As can be seen in the presented results (Table 4) there are no much differences in the residual deformation when varying the orientation of the fibres.

4. DISCUSSION AND CONCLUSIONS

The use of Finite Element Analyses (FEA) is one of the most used techniques to predict the behaviour of structures. FE software like LS-DYNA has been proved capable of, with relative accuracy, model explicit dynamic situations. In this work we started by calibrating the geometric and material model by comparison with the experimental results obtaining a difference of 2% between both cases. After proper calibration the behaviour of three different crack possibilities were compared and concluded that there is no significant influence in the residual deformation of this thin steel structure when varying the orientation of the crack.

To study the possibility of repairing this kind of structures several different possibilities were considered for the CFRP patch. In this part of the study we concluded that the thickness of the patch and the orientation of the fibres have no significant influence in the residual deformation. As for the size of the FRP patch it was shown that there is an optimum size for the FRP patch that produces the minimum residual deformation.

Figure 13 represents the behaviour of the general three situations studied, the un-damaged situation, the damaged situation and the repaired situation. It is shown that repairing with FRP patch can improve the behaviour of the thin steel structure almost to the point of the un-damaged one.

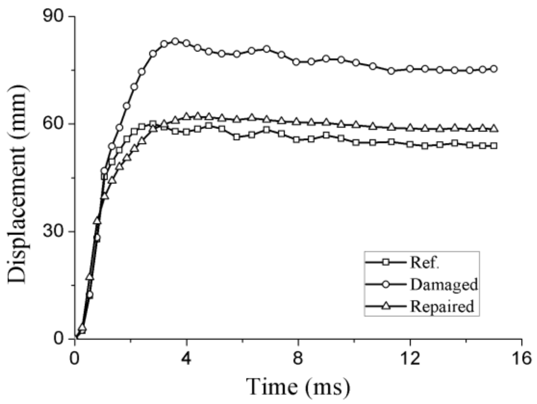

Figure 13 - Comparison of the three general situations studied.

Explicit dynamic simulations are still in an early stage of development as many of the modelling possibilities for the implicit analysis are not yet available for the explicit analysis. Blast loading simulating still needs to concentrate the attention of researchers in terms of the material properties for high strain-rate situations. The commercial codes should be improved too in terms of available element types and material models.

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