Validating dynamic crush response of unidirectional carbon fibre tube via finite element analysis method using LS-DYNA

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Abstract. Crashworthiness of composite structures is of significant interest to manufacturers and operators as composites become more commonly used in automobiles and aircraft. Experimental crush testing remains an important tool in the design of subfloor fuselage structures for crashworthiness, as numerical simulations are still largely unable to accurately predict the crushing response of complex composite structures. In this paper, dynamic crush testing of carbon-fibre/epoxy specimens experimental result is validated using the modelling and simulation software LS-DYNA to understand impact behaviours under dynamic loading for finite element simulations. The tubular finite element model was modelled using MAT54 and was impacted by a 65KG rigid wall impactor with an impact velocity of 55 km/h. Material card parameters were evaluated to understand crush behaviour of the FE model. Upon analysis the experimental results and the FEA results showed a good correlation. Modelling criteria used for this model can be further used to simulate crush response of unidirectional carbon tubes under dynamic impact.

1. Introduction
A well-designed carbon fibre part has better energy absorption capability compared to metallic energy absorbing structures [1, 2]. Hence, in various sectors of the automotive industry Carbon – Fibre composites are being used as crush energy absorbers for improvised impact energy absorption during collision [3-6].

Under impact, progressive crushing of axially loaded metallic tube structures occurs via plastic buckling which is referred to as progressive folding [7]. Whereas in case of carbon fibre structures it occurs via brittle fracture and is referred to as progressive crushing if, the crush is guided [8]. Guided crushing of carbon fibre structures does not only depend on material structure but can also be accomplished by changing component geometry as geometrical changes can affect the failure mechanism thus causing change in energy absorption levels [9]. Since the energy absorption mechanism varies based on the part’s geometry and features, its design methodology is also distinctively different. Cross sectional features and stacking sequence of the carbon fibre highly affects the energy absorption capability and fracture behaviour of the carbon fibre part [10]. Unlike simulation of metal structures, simulation of composite structures is deemed to be more complex as the model’s parameters needs to be examined and studied to assure that the model replicates real life test behaviour with the right...
parameters. Nevertheless, the part’s crush and mutual interaction behaviour can be predicted through numerical finite element simulation software’s such as LSDYNA, ABAQUS Explicit, PAM-CRASH and RADIOSS which uses explicit integration formulation for generating results. However, ample simulations are required to find the apt criteria for modelling.

Many studies have investigated on these parameters for modelling and validating real life test behaviour of carbon fibre composites. However, only limited research data is available on validation of dynamic guided progressive crushing of carbon fibre composite using a double sided plug.

In this paper, explicit finite element code LS-DYNA has been utilised for comparing and evaluating performance of guided crushing of a carbon fibre tube with double sided plug. It aims to examine and validate the ability of the LS-DYNA software to depict progressive crush absorption response of the carbon fibre tube. The LS-DYNA software is widely used to perform explicit dynamic post-failure simulations [11]. Several studies of carbon fibre composite impact modelling has been performed using the pre-existing material models such as MAT54 in LS-DYNA as it closely depicted the characteristics of carbon fibre [12] Hence, the material card used for validation the model for this research is the *MAT_ENHANCED_COMPOSITE_DAMAGE (MAT054). The study investigates on how material card parameters affects the crush performance behaviour or carbon fibre. Depending on analysis results, the study proposes suitable simulation criteria that could be used to model unidirectional carbon fibre tubes under dynamic loading. The model can be used as a base model to select apt parameters for achieving optimum dynamic crush response behaviour. The main focus of the study is achievement of progressive crush behaviour through unidirectional fiber delamination. For the study, parameters such as material geometry, impactor speed and impactor mass are defined however, the models design parameters involving material card and boundary conditions are evaluated for apt impact response.

The final simulation results are compared with the dynamic crush test experimental results obtained from Ueda et al. [13] to validate if the simulation model depicts same behaviour as the experimental model.

Design dimensions and test results for the model constructed in this paper is extracted from an existing journal article published [13] where they used a double-sided plug for controlled and improvised energy absorption. The two-piece double-sided plug constrains the outer and inner walls of the carbon fibre tube which under crush conditions allows the damaged fibre to eject through the built cavity.

2. Experiments and results
Experimental test results for validation were obtained from an existing published [13]. The test specimen was a circular CFRP tube fabricated from a PYROFIL TR30S/#380, Mitsubishi Rayon prepreg sheet. The prepeg sheet was wrapped onto a 50 mm inner diameter aluminium mandrel which was then covered using a heat resistive film. Twelve prepeg sheets were stacked onto the aluminium mandrel and the stacking sequence was unidirectional with about 60% fibre volume fraction. Under vacuum conditions, the prepeg sheet was cured for 80 minutes at 130°C. Once cured the aluminium mandrel was removed and the consolidated carbon fibre tube which had a thickness of 2.9 mm and was cut into 80 mm length sections.

To increase energy absorption of the carbon fibre part, an outward-splaying and inward-folding double sided plug was used. The double sided plug which was attached to the base of the CFRP tube ejected the fractured part through its gaps preventing blooming failure and moderating peak force which is generally observed at the beginning of fracture.
The experimental test data considered for this report is the dynamic test results at 55 km/h. The double-sided plug used for this test has an inner radius curvature of 8 mm and outer radius curvature of 5 mm. Experimental test result data is shown in figure 2. From the experimental data it was observed that the average crush forces was about 10kN.

![Figure 1. Assembly drawing of the double-sided plug for a circular CFRP tube [13]](image)

3. FEA analysis of the CFRP plug

3.1. 3D modelling

The model and the plugs were initially designed using Autodesk Inventor which is a 3D modelling platform. The part was designed as a ‘sheet metal’ which behaves as a thin flat piece of metal with uniform thickness throughout the entire part. The advantage of the sheet metal design is that when the model is exported to LS-PREPOST for meshing it can easily be defined as a ‘shell element’. Since Autodesk Inventor has a much approachable user interface for 3D designing it was preferred over designing using LS-PREPOST.

Upon completion of the 3D model it was exported as a STEP file and then imported into LS-DYNA. The simulation software used to depict failure of the modelled CFRP tube was LS-DYNA. However,
initial drawings were done using Autodesk Inventor which was then exported to LS-PREPOST. The inventor ‘sheet metal’ STEP files were imported to LS-PREPOST and a thickness of 2.9 mm was set for the CFRP tube. Meshing of the model was done using LS-PREPOST and each parts (CFRP tube and plugs) were individually meshed. The CFRP tube was given a fine mesh of 0.5 mm whereas the double-sided plugs were given a slightly coarse mesh of 1.5 mm.

![Figure 3. 3D model components](image)

### 3.2. Material Card

According to [12, 14], MAT54 can successfully be used to simulate axial crushing behaviour of a sinusoidal composite specimen. The model can accurately capture the peak and average crush force, overall load-displacement response and most importantly it exhibits stable and progressive element failure and deletion. Hence, the material card used for the CFRP tube was MAT 54 (MAT054_ENHANCED_COMPOSITE_DAMAGE), which is widely used for dynamic test performance of CFRP tubes. The part had 12 layers of CF sheet layered around it and this was simulated using the option PART_COMPOSITE and a specific thickness of 0.24166 mm was given for each sheet. The complied thickness of 12 such sheets would add up to the original thickness of 2.9 mm.

### 3.3. Boundary conditions

The impactor for the model was designed to be rigid wall to reduce computational time. The wall was assigned a mass of 65 KG (6.5E-2 ton) and velocity of 55 km/h (15300 km/mm). A small distance was kept between the CFRP tube and impactor to replicate the initial hit and a coefficient of friction of 0.3 was given.

![Figure 4. Rigid wall impactor set up](image)
The control cards used for the model were mainly for hourglass, termination and timestep. The hourglass was set as LSDYNA standard itself of 0.1. The termination ENDTIM was set to be 4.92E-3 and ENDMAS was set to be 1.0E8. For the model to be reliable the percentage increase should be less than 5% for mass scaling. This data can be found in the d3hsp file when opened in a WordPad. In the added mass calculation, the model should show less than 5% percentage increase [15]. In this section we have achieved a percentage increase of 2.1% which is exceptionally good.

| Calculation with mass scaling for minimum dt |
|---------------------------------------------|
| Added mass                                  | 1.3759E-06 t |
| Physical mass                               | 6.5145E-02 t |
| Ratio                                       | 2.1120E-05   |
| Added mass                                  | 1.3759E-06 t |
| % Increase                                  | 2.1121E-03 % |

The timestep used for the model is -1.0687E-7 with a TSSFAC value which is scale factor for computed time step value of 0.9. The contact set between the plugs, CF part and the impactor was ‘automatic surface to surface contact’ (CONTACT_AUTOMATIC_SURFACE_TO_SURFACE).

In crash analysis, predetermination of where and how contact will take place may be difficult or impossible as the deformations can be exceptionally large at times. Due to this, LSDYNA recommends the automatic contact options as these contacts are non-oriented, meaning they can detect penetration coming from either side of a shell element. Hence, the contact card used for contact between the CFRP tubes and the plugs and the impactor and the CFRP tube is CONTACT_AUTOMATIC_SURFACE_TO_SURFACE. The CFRP tube was set as the master side as it had more nodes than the support plugs.

![Figure 5. Cross-sectional view of the part](image-url)
4. Results

The simulated crush pattern represented the original shattering behaviour of the CFRP tube. The crush initiated at the bottom of the plug when it hit the curved surface of the lower plug and propagated upwards like a shock wave. Close observation on the initial crush behaviour also portrayed delamination properties of CFRP tubes. However, due to element deletion it did not visually portray the damaged strands. An illustration of crush behaviour between the experimental model and simulation model is shown in figure 7.

Figure 6. Crushing of the CFRP tube in LSDYNA

Figure 7. Comparison between original model and simulation model

The model represented the working mechanism of the real-life test model as it sheared in the strong X ply direction.
Figure 8. Crack initiation at 0.000100 sec

Figure 9. Crack initiation at 0.000220 sec

Figure 10. Crack propagation at 0.004300 sec
Once the visual simulation results correlated with the real life model a load vs. crush-length graph was generated to compared experimental and simulation results.

![Experimental Load vs. Crush-length graph](image)

**Figure 11. Dynamic test result of simulated model**

From the above graph it was observed that the average force of the graph in the simulated model is about 11 kN and in the real life model average force was approximately 10 kN. A good correlation has been established between the real life model and the simulated model.

It is also noteworthy that the simulation model’s delaminated fiber strands and the real life models delaminated strands were not visually identical. However, the results showed a good relationship because when carbon fibre physically disintegrates it loses structural stiffness and that’s why delamination in the FE model does not affect simulation results. Although the visual data was not fully as expected the numerical data correlated very well. A comparison of both experimental and simulation results is shown in figure 12.

![Comparing experimental and simulation Load vs Crush-Length graph](image)

**Figure 12. Comparing experimental and simulation results**
5. Conclusion

The main aim of the study was to validate dynamic crush response behaviour of carbon fibre via finite element simulation. In order to attain this aim, three objectives had to be achieved.

1. Selecting the right material card and obtaining apt material card parameters.
2. Defining boundary conditions to replicate real-life experimental setup.
3. Validating simulation data with experimental data.

From the results a good visual and graphical correlation was obtained between the experimental and simulation model. Hence, it can be concluded that MAT54 portrays real-life dynamic crush behaviour of unidirectional carbon fiber tubes and contact forces can be simulated using AUTOMATIC_SURFACE_TO_SURFACE_CONTACT. For future research, researchers could use these simulation parameters to analyse dynamic crush response of carbon fibre tubes.

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