Numerical investigation of parameters affecting crush mode of triggered FRP tube

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Abstract

When a quasi-static axial compressive load is applied to a Fiber Reinforced Plastics (FRP) tube, a continuous and stable fracture phenomenon called “Progressive Crushing” which shows highly effective energy absorption appears. The authors have constructed a cohesive element FEM model that can reproduce the process to this phenomenon. The purpose of this paper is to investigate the most stable chamfer shape for progressive crushing of the FRP tube, by using Cohesive Zone modeling technique. In the study, cross-sectional shapes of triangle type, chevron type and M-type were selected for the simulation of axial crushing test to confirm crush mode. Five geometric shapes of flat plate FEM model were considered to conducting a fundamental investigation. Furthermore, the 3D finite-element models of FRP tube using reasonably cross-sectional shapes were intended to obtain a well-balanced chamfer shape, therefore, providing useful suggestions for FRP tube design and/or manufacture.

1 Introduction

An energy absorption structure in a vehicle, namely “Crush Box”, is designed to be installed behind the bumper as a specific energy absorbing device. In recent years, fiber reinforced composites have been demonstrated the considerable potential for lightweight energy absorbing structures, according to experimental research and numerical simulation. In particular, the crushing process of composite tubular structures has been investigated by many of researchers. The studies examined the parameters which influence composite tubes crushing mode, such as material properties, geometry design, laminate design, interlaminar fracture toughness etc. Higher energy absorption is also known as ”Progressive Crushing” [1] [2], which occurs when an FRP tube with trigger part is crushed in the axial direction. This phenomenon is expected to be applicable to car crush boxes.

Many experimental surveys are reported that geometric shape influences the energy absorption capability of FRP tubes [3]. Also, many of axial crushing tests with various types of triggered tube have been performed, where the failure modes and specific energy absorption have been observed [4] [5]. Palanivelu et al. reported the quasi-static crushing performance of nine different geometric shapes of composite tubes by 144 tests for their specific applications [6]. With the quantitative data analysis, they concluded that the progressive crushing phenomena of composite tubes depended upon the designed geometric shapes.

Recently, numerical simulations attract the attention of the composite materials industry, and it is recognized this procedure come to able to reduce the manufacturing costs and time by providing its analysis before actual production.

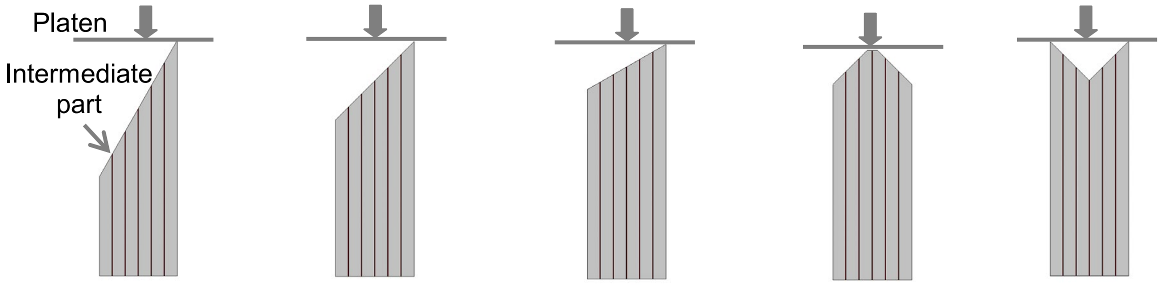
In the author’s previous study, , an axial-crushing test of FRP tube was carried out, and a flat plate FEM model with cohesive element of LS-DYNA has been constructed to reproduce the process up to progressive crushing [7]. According to our finding, the cohesive element model of LS-DYNA is sufficiently accurate to simulate the initial fracture of the FRP tube.

In the study, five geometric shapes of flat plate FEM model have been considered to conducting a fundamental investigation, by using Cohesive Zone modeling technique. First, simple models were used to confirm the most basic fracture modes. The flat plate FEM model with cross-sectional shapes of triangle type, chevron type and M-type were selected for the simulation of axial crushing test to examine the crush mode. Second, 3D finite-element models of FRP tube using reasonably cross-sectional shapes were intended to obtain a well-balanced chamfer shape.

2 Numerical investigation method

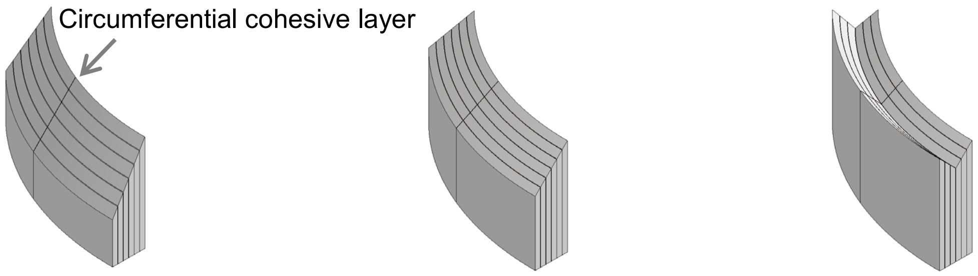
2.1 Finite-element models of FRP tube

In this paper, the authors would like to divert some basic data a portion of the previous studies, thus material properties and/or model configuration, creating a base finite-element model for the numerical investigation. According to the results of the aforementioned FRP tube test, the delamination between the laminated layers was caused by separation due to the normal and shear forces. In view of previous work, six resin layers and five cohesive layers were constructed in the model. In order to confirm the fracture behaviors on the energy absorption, five different geometric plate models with triggered part have been chosen (Fig.1). Cross-sectional shapes of triangle type, chevron type and M-type were selected for the simulation of axial crushing test to investigate the crush mode. The height, width and thickness of the plate-model are 15mm, 5mm and 0.8mm, respectively. The 3D finite-element models of the FRP tube using three cross-sectional shapes are shown in Fig.2. These 3D models consist of one-eighth of the tube's circumference, as the rest of the tube can be interpolated by symmetry. In order to simulate fracture in the thickness direction, one circumferential cohesive layer is laid on.



(a) Triangle type-30° (b) Triangle type-45° (c) Triangle type-60° (d) Chevron-type (e) M-type

Fig.1: Plate models of triggered FRP tube and loading condition



(a) 3D Triangle type-30° (b) 3D Triangle type-45° (c) 3D M-type

Fig.2: 3D models of triggered FRP tube

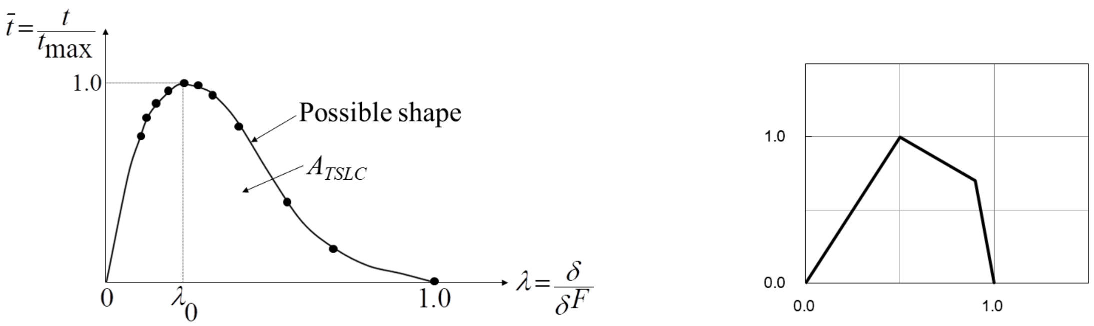
2.2 Cohesive element for fracture simulation with LS-DYNA

In this study, cohesive element for fracture modeling with LS-DYNA is applied. The fracture mechanics based Cohesive Zone Modeling technique of LS-DYNA is appropriate for delamination or crack numerical simulation. The cohesive zone model uses a failure mechanics approach, which is based on energy release rates in the modeling of delamination of composite material. It is capable of inputting the fracture toughness values and crack propagation characteristic parameters in FEM model. Several related material model described in the software LS-DYNA are listed here.

*MAT_COHESIVE_MIXED_MODE (138)
*MAT_COHESIVE_ELASTIC (184)
*MAT_COHESIVE_GENERAL (186)

*MAT_COHESIVE_MIXED_MODE_ELASTOPLASTIC_RATE (240)
*MAT_USER_DEFINED_MATERIAL_MODELS (041-050)

As seen from the above list, there are several ways to model delamination or crack with LS-DYNA. In our studies, MAT_COHESIVE_GENERAL (common named MAT_186) has been chosen because the effect of strain rate on the deformation mechanisms and the corresponding deformation patterns have not been considered in our previous tests.
The cohesive zone material model, MAT_186 can be employed to describe the failure of composites simply. This model includes three general irreversible mixed-mode interaction cohesive formulations with arbitrary normalized traction-separation law given by a load curve (TSLC) as shown in Fig.3. The interaction between fractures Mode I and Mode II are considered [8].



(a) Common normalized traction-separation law (b) TSLC curve of the numerical model

Fig.3: Normalized traction-separation law (TSLC) of MAT_186

2.3 Material properties

The macroscopic mechanical property of GMT sheet will be assumed as isotropic for numerical investigation in the study. The glass mat of GMT composite is considered as a quasi-isotropic and elasto-plastic material. The MAT_024 (MAT_PIECEWISE_LINEAR_PLASTICITY) which is a common material model for quasi-isotropic and elasto-plastic definition is chosen from the material model library of LS-DYNA. The physical properties are given in Table 1. The mechanical properties of the cohesive element used for the intermediate part between the glass mat layers are shown in Table 2. These material properties are diverted from the author's research [7].

Material property	In-plane direction
Elastic modulus (MPa)	5570
Shear modulus (MPa)	2140
Strength (MPa)	87.4
Breaking extension (%)	2.15

Table 1: Material properties of GMT composite [7]

Material property	Values
Interlaminar tensile strength T (MPa)	39
Interlaminar shear strength S (MPa)	39
Energy release rate for mode I G_I (N/mm)	3.0
Energy release rate for mode II G_{II} (N/mm)	3.0

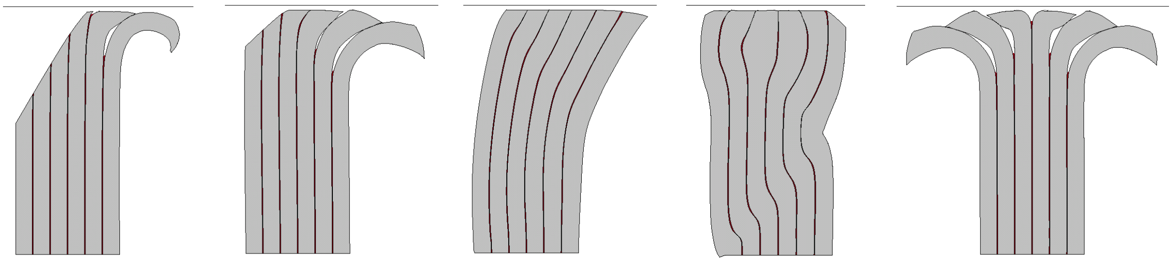
Table 2: Properties of intermediate part for cohesive element [7]

3 Investigation results and discussions

The fracture behaviors of all the FRP tube models were invested for quasi-static axial compressive loading condition with a rigid platen. Based on the numerical investigation results extracting from the various types of triggered FRP tube, the crushing characteristics and the load-displacement plots of 3D models are shown in this section.

3.1 Plate models

Fracture behaviors of all the plate models are shown in Fig.4. The fracture mode of Triangle type-30°, Triangle type-45° and M-type are close to the "progressive crushing mode" at the initial stages. Especially, the M-type model has been separated into inwards and outwards by lamina bending followed by resin bonds. The crushing performance of Triangle type-60° and Chevron-type models are tipped toward the same direction, making it difficult to generate the progressive fracture mode.



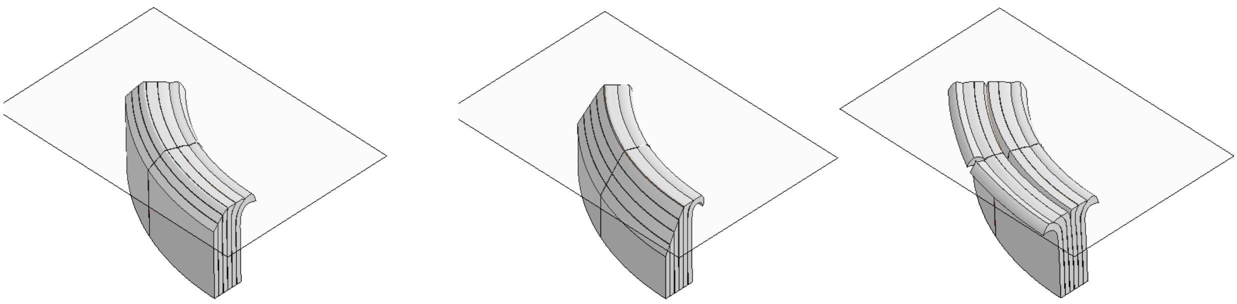
(a) Triangle type-30° (b) Triangle type-45° (c) Triangle type-60° (d) Chevron-type (e) M-type

Fig.4: Fracture behaviours of plate models

Due to the above failure modes, the cross-sectional shape of Triangle type-30°, Triangle type-45° and M-type are recommended for 3D models to investigate the influence of fracture behaviors followed the geometric shape of triggered FRP tubes. Additionally, for M-type, there is more number of cracks between layers, which has a potential to absorb more energy.

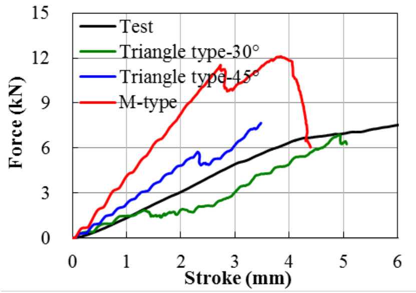
3.2 3D circumferential models

Fracture behaviors of all 3D circumferential models are shown in Fig.5, and the load-displacement plots of these models are shown in Fig.6 (a). The previous test F-S result is also drowning in the graph for reference. The cross-sectional shape of triggered FRP tube using the test was Triangle type-45°, and some pictures of the test as shown in Fig.6 (b).

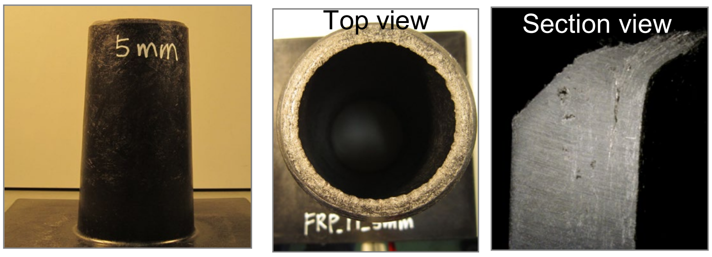


(a) 3D Triangle type-30° (b) 3D Triangle type-45° (c) 3D M-type

Fig.5: Failure behaviours of 3D models



(a) Load-displacement plots



(b) Test results of the FRP tube with 45° trigger

Fig.6: Load-displacement plots by simulation and test results of the FRP tube

The fracture pattern of Triangle type-30°and Triangle type-45° model was very similar at initial stage. Both of them exhibited the similar crushing mode to the test result. However, the crushing load value of the Triangle type-30° was lower than other models, the energy absorption capability may tend to reduce. The similar tendency was stated in the experimental research for Triangle type-30° tube [5].

The crushing load of the M-type had most high at initial fracture load as compared to others. Reason for the high crushing load is that the deformation and fracture area is larger than other shapes. However, according to the test result of CFRP under axial compression by Ueda et al. [4], V-shaped trigger can reproduce stable continuous failure after the initial stage crushing. Therefore, it is inferred that the M-type triggered FRP tube will be in the similar failure mode after the initial stage fracture.

Fracture behaviors of 3D circumferential model of M-type are shown in Fig.7. The axial cracks were formed parallel to the axis of the tube. Subsequently, the circumferential delamination was started. Center crack was formed before the circumferential delamination appeared. The simulation results exhibited a very stable and progressive crushing throughout the crushing process. It will lead to great increase of their energy absorption capability, due to the macro-failure mechanisms associated with axial cracks, center crack, lamina bending and circumferential delamination.

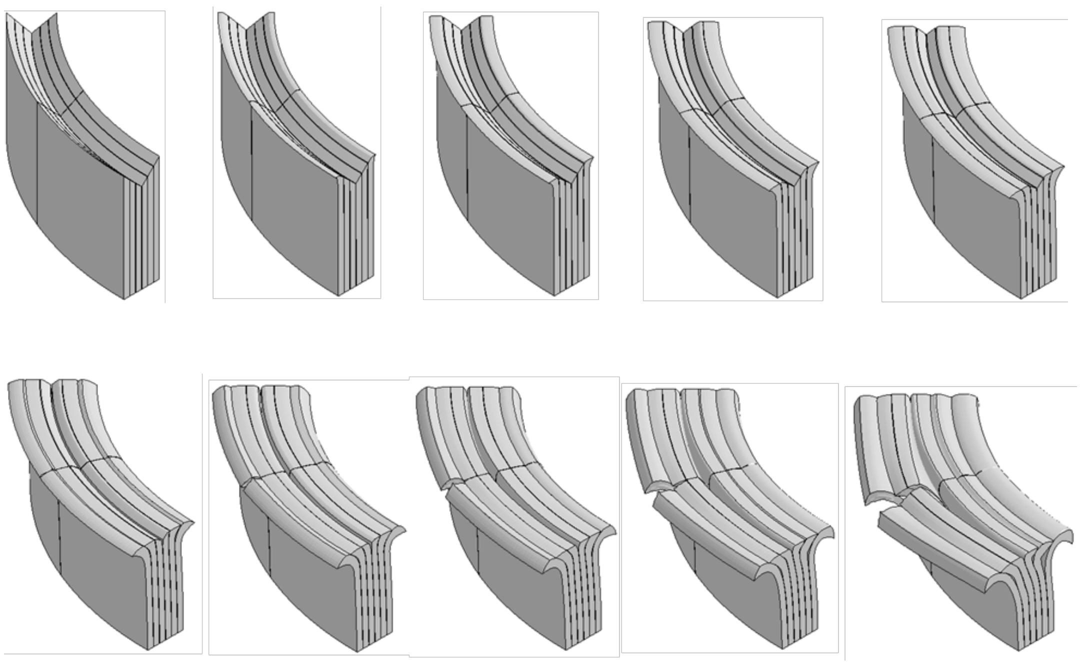


Fig.7: Failure behaviours of 3D M-type model

4 Conclusions

In this paper, a numerical investigation of triggered FRP tube was carried out using Cohesive Zone modeling of LS-DYNA, for searching the most stable chamfer shape possessing “Progressive Crushing”. Cross-sectional shapes of triangle type, chevron type and M-type were selected for the simulation of axial crushing test to examine the crush mode. Five different geometric flat plate models and three 3D models of FRP tube were considered to conducting the numerical investigation.

The well-balanced chamfer shape for progressive crushing was obtained from the investigation. In the case of M-type triggered model, fracture progress and failure behavior was stable. It can be inferred that M-type trigger shape is effective to reproduce continuous and stable fracture phenomenon.

With the greater accuracy allowed by such a model, it would be of assistance when designers vary triggered type of FRP tubes to produce composites with improved energy absorption capability.

5 Literature

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