

Crushing Analysis and Lightweight Design of Tapered Tailor Welded Hybrid Material Tubes under Oblique Impact

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ABSTRACT

The increasing demand for lightweight design of the whole vehicle has raised critical weight reduction targets for crash components such as front rails without deteriorating their crash performances. To this end the last few years have witnessed a huge growth in vehicle body structures featuring hybrid materials including steel and aluminum alloys. In this work, a type of tapered tailor-welded tube (TTWT) made of steel and aluminum alloy hybrid materials was proposed to maximize the specific energy absorption (SEA) and to minimize the peak crushing force (PCF) in an oblique crash scenario. The hybrid tube was found to be more robust than the single material tubes under oblique impacts using validated finite element (FE) models. Compared with the aluminum alloy tube and the steel tube, the hybrid tube can increase the SEA by 46.3% and 86.7%, respectively, under an impact angle of 30°. Parameter analyses were performed to reveal the influence of four geometrical variables on the crashworthiness of the TTWTs. In addition, the radial basis function (RBF) metamodels were built for the SEA and PCF of the TTWTs, while the non-dominated sorting genetic algorithm (NSGA-II) was used to achieve the optimal solutions of the tube under oblique impact loads. The results show that the optimal solutions are different under different load angles and the solutions considering multiple load angles show more robust crashworthiness performance against oblique impacts. The proposed tapered hybrid tube has a potential application on vehicle bodies with improved crash performances under oblique loads.

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INTRODUCTION

To meet the increasingly stringent regulations on passenger cars for fuel efficiency and emission limits, lightweight potentials of the car body have been tapped throughout the design process. One remaining challenge in developing lightweight car bodies is to balance their weight reduction and crashworthiness.

In vehicle frontal crashes, including the oblique and offset impacts, the frame front rail plays a significant role in energy absorption and force transmission to the passenger compartment. Therefore, crashworthiness and lightweight design of the front rails has been investigated by many researchers.

One practical consideration in front rail design is to improve its robustness against oblique loads, which occur more frequently than pure axial load in real-life accidents. In the US, vehicles are required to provide enough protection to occupants at any impact angle up to 30 degrees [1]. As an effective structure against oblique loads, tapered tubes have been investigated by several researchers. Experimental and numerical analyses were first conducted by Nagel and Thambiratnam [2, 3, 4] to compare the energy absorption of straight and tapered thin-wall tubes under axial and oblique collapse.

They found that the tapered tubes absorb more energy than the straight tubes under oblique static loads. Qi et al. [5,6] showed through numerical simulations that tapered tubes can absorb more energy than their straight counterparts under dynamic loads with large loading angles.

For further improved performance, multi-objective optimization design (MOD) along with meta-modeling techniques have been employed in crashworthiness designs [7,8]. For example, Qi et al. [5,6] investigated multi-objective crashworthiness optimization of empty and foam-filled conical tubes and square tubes under oblique impact. Li et al. [9] adopted the multi-objective optimization method to seek optimal designs for foam-filled tubes under multiple load cases. However, all these work had been focused on thin-walled tubes made of a single material such as steel or aluminum alloy.

More recently, with the advancement of joining techniques of dissimilar materials such as the friction-stir welding, thin-wall structures made of hybrid materials have emerged and shown promising applications in vehicle crash safety. For example, Zhou et al. [10] studied the crashworthiness of an S-shaped front rail made of steel-aluminum hybrid materials. Their results showed that the use of

steel-aluminum hybrid materials can significantly improve the crashworthiness and lightweight of the S-shaped front rail. Gedikli performed numerical simulations for the dynamic pure axial impacts of empty [11] and foam-filled [12] tailor-weld tubes (TWTs). Results showed that the absorbed energy and crushing force can be favorably adjusted by choosing the TWTs with different materials and thickness. Reyes and co-workers [13, 14, 15] performed crash tests on obliquely loaded empty and foam-filled thin-walled extrusions made of aluminum alloys. Different tempers have been discussed and proven to be an important parameter in affecting crashworthiness of such structures. To date, crushing analysis and lightweight optimization of thin-walled tubes made of dissimilar materials under oblique loads are not available in the literature to the best of authors' knowledge.

This study aimed at investigating the crashworthiness of a group of tapered tailor-welded tubes (TTWTs) with steel-aluminum hybrid materials under oblique impact loads. These tubes can be potentially used as the frame front rail of a passenger vehicle (see figure 1) to improve its crashworthiness under oblique impact, and at the same time to reduce the body weight. For simplicity, locating holes, derivational grooves and irregular sections of the frontal rail were neglected in the modeling. The front portion of the rail, as circled in Figure 1, was the part where the TTWT found its application. Nonlinear finite element (FE) code LS-DYNA was used for this purpose. After the validation of finite element model and comparison of oblique crashworthiness between tubes made of single material and hybrid materials, the influence of several key factors, including wall thickness of two parts, the Length ratio of the aluminum tube and the tapered angle, on the crash behavior of the structure was analyzed. And multi-objective optimization method was employed to determine optimum values of the material and geometric parameters for two crashworthiness criteria, SEA and PCF. The results of TTWTs with steel-aluminum hybrid materials under a specific angle were added by an assumed weight to take impact angle uncertainty into account, thereby showing its advantages for potential engineering applications.

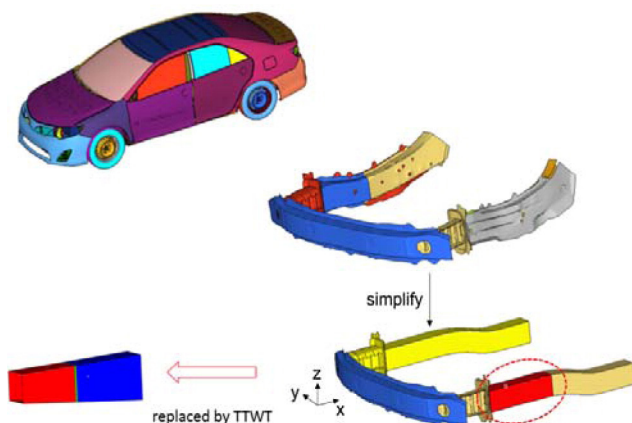


Figure 1. Application of TTWT on frame front rail of a passenger car.

MATERIALS AND METHODS

Crashworthiness Criteria under Oblique Impact

Several key criteria are generally used to evaluate the crashworthiness of energy absorbing structures such as the thin-walled tube. These criteria include the energy absorption (EA), the specific energy absorption (SEA) and the peak crushing force (PCF).

EA is recognized as a measures of the strain energy absorption of a structures through plastic deformation, which can be determined as follows:

$$EA = \int_0^d F_{(x)} dx \quad (1)$$

where $F_{(x)}$ is the instant crushing force at a deflection of x on the crushing force-deflection curve, and d is the effective deflection, which is taken as 70% of the total length of the tube in the current study [5].

SEA is defined as the ratio of the total energy absorption to the mass, m , as:

$$SEA = EA / m \quad (2)$$

To account for both axial and oblique load cases, composite crashworthiness indexes, SEA_α and PCF_α , were proposed by Qi et al. [5], which are defined as follows:

$$PCF_\alpha = \max(PCF^{\alpha_i}) \quad (3)$$

$$SEA_\alpha = \sum_{i=1}^n SEA^{\alpha_i} W^{\alpha_i} \quad (4)$$

where α is the load angle, and it is noted that the maximum PCF occurs when load angle is 0° , i.e., pure axial. SEA^{α_i} denotes the SEA value under the i th load angle, α_i , W^{α_i} and is the corresponding weighting factor under this load angle. Different series of W^{α_i} can be used to obtain different SEA_α with a focus on different load angles. And the normalized weighting factors can be defined as:

$$\sum_{i=1}^n W^{\alpha_i} = 1, W^{\alpha_i} \geq 0 \quad (5)$$

Material Model

The tapered tubes under consideration were made of two types of materials, i.e., aluminum alloy AL6061-T6 and cold drawn steel AISI1018. The composition of the weld line was regarded as a mixture of aluminum alloy and steel. The mechanical mixtures take place at the weld interface since the two sheets are rubbed hard against each other. Different ratios of individual components exist in the weld line because of their different melting temperatures. The properties of the friction-stir dissimilar welding interface were given as [16]:

$$X_w = (0.6)X_{AL} + (0.4)X_{STEEL} \quad (6)$$

where the subscripts W, AL and STEEL represent the weld, aluminum alloy and steel, respectively. Since steel diffuses less than aluminum in the weld seam, a ratio of 0.4 for steel and 0.6 for aluminum was applied [11,16]. Johnson-Cook model was adopted to describe the constitutive relationship of all the materials under high velocity impact. Those significant factors, such as strain rate, strain hardening, and temperature effects, are taken into account to express the equivalent stress, σ_{eq} as follows [17]:

$$\sigma_{eq} = [A + B\epsilon_p^n][1 + c \ln(\dot{\epsilon}^*)][1 - (\frac{T - T_0}{T_m - T_0})^m] \quad (7)$$

where A , B , n , c and m are material constants, ϵ_p is the accumulated plastic strain, $\dot{\epsilon}^*$ is a dimensionless strain rate which is equal to $(\dot{\epsilon}_p/\dot{\epsilon}_0)$, $\dot{\epsilon}_p$ is the plastic strain rate and $\dot{\epsilon}_0$ is the reference strain rate with the value of 1 s^{-1} , T_0 and T_m are the reference and melting temperatures, respectively. The material properties and constants of the Johnson-Cook models for the two materials and the weld line are listed in Table 1.

Table 1. Mechanical properties and J-C model constants of Al6061-T6, AISI1018 and weld [11]

Material	Johnson-Cook material constant					Material properties	
	A (MPa)	B (MPa)	C	n	m	Density (kg/m ³)	E (GPa)
AL6061-T6	289.6	203.4	0.0110	0.350	1.340	2850	72
AISI1018	520.0	269.0	0.0476	0.282	0.553	7850	200
Interface material	382.0	230.0	0.0260	0.323	1.140	4850	123

Computational Model

The structures considered in this study are tapered tailor-welded tubes (TTWTs) as shown in Figure 2. The specimens comprised of two parts: the front part and the rear part, which were made of AL6061 T6 and AISI1018, respectively. Friction stir welding [18] was applied to join the two parts of the hybrid material tube with a 4 mm wide weld seam [12]. All the tubes have a rectangular cross section and baseline dimensions of length $L = 300 \text{ mm}$, fixed-end side length $A = 80 \text{ mm}$, $B = 100 \text{ mm}$ and a tapered angle $\theta = 2.5^\circ$, as shown in Figure 2. The length ratio of the aluminum part $n = 0.45$, which means the length of the aluminum part accounts for 45% of the total length, L . The thickness of both parts was set as 1.4 mm in the baseline to exclude the influence of thickness gradient under oblique impact [19]. An average thickness of the two parts was applied to the weld zone in cases when the two parts have different thicknesses. Previous study has shown that the weld line does not have a significant impact on the formability of aluminum-steel tailor weld blanks because of its small volume and the gradient in mechanical properties between the sheets [16]. The tubes were clamped at the largest end and crushed by a rigid wall with a constant velocity of 35mph and a prescribed load

angle α , which ranged from 0° to 40° with an increment of 10° . The schematic diagram of the computational model is also shown in figure 2.

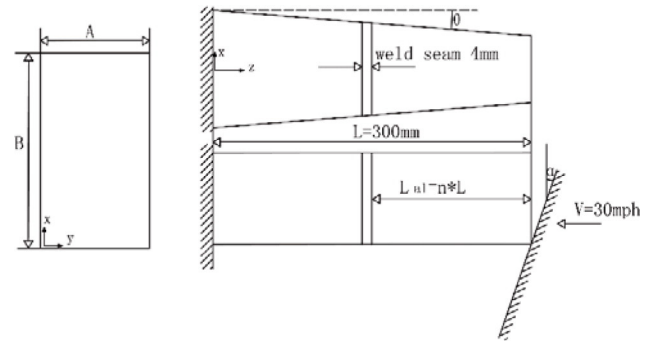


Figure 1. Tube dimensions and schematic of the computational model.

Numerical simulations of the problem were carried out using the nonlinear explicit FE code LS-DYNA. The tubes were modeled with Belytschko-Tsay four-node shell element with five integration points through the thickness and one integration point in the element plane. A featured element size of 3 mm was used to balance the simulation accuracy and computational cost. An 'automatic single surface' contact algorithm was employed to account for the self-contact of the tube wall and an 'automatic node to surface' algorithm was defined for the interface between the tube and the rigid wall. Both static and dynamic friction coefficients were set as 0.2.

RESULTS AND DISCUSSION

Validation of FE Modeling Methods

To validate the FE modeling methods used in this study, axial crushing behavior of a circular tailor welded tube made of hybrid materials was simulated and the numerical results were compared with the experimental results in Ref. [11]. The geometric and material parameters of the tube are the same as those in the reference while the size of weld seam was set to 4mm. Figure 3 compares the numerical and experimental results of the crushing force time history of the tube under pure axial collapse. Good agreement between the two sets of data can be observed except that the numerical result shows a forward shift relative to the experimental curve. This may be explained by the fact that the plate used to crush the tube in the test was not a rigid wall as assumed in the FEA. The PCF values of numerical result and experimental result are 63.29 kN and 66.12 kN, respectively. The computational value is over-predicted by 4.27%, which is assumed to be acceptable. To quantify the error between the computational and experimental data, a validation metric proposed by Oberkampf and Trucano [20] was used. With the assumption of zero experimental error, the validation metric, V , is defined as follows:

$$V = 1 - \frac{1}{t_{\max}} \int_0^{t_{\max}} \tanh \left| \frac{F_N(t) - F_E(t)}{F_E(t)} \right| dt \quad (8)$$

where F is the crushing force and $t_{\max}$ is the maximum crushing time of the tube. The relative error, given in Ref. [6], is defined as:

$$Error = \frac{1}{t_{max}} \int_0^{t_{max}} \left| \frac{F_N(t) - F_E(t)}{F_E(t)} \right| dt \quad (9)$$

The validation metric and the relative error in this case were 62.32% and 38.65%, respectively, as provided in Table 2.

Table 2. FE model validation assessment based on experimental results[11] for a TWT under axial impact.

L (mm)	D (mm)	T (mm)	n	PCF _E (kN)	PCF _N (kN)	SE _{PCF} (%)	V (%)	Error (%)
80	40	1.5	0.5	65.12	63.29	4.27	62.32	38.65

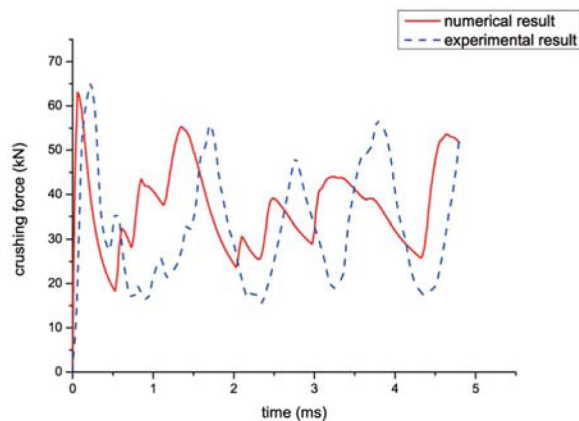


Figure 3. Numerical and experimental results [11] for the tailor welded tube of AL6061&AISI1018.

Therefore, the FE modeling methods regarding the mesh size, element formulation, integration point and contact algorithms, etc., of this particular study were adequate and the developed FE models of the TTWTs are competent to be used for the subsequent analysis and design optimization.

Comparison of Three Types of Tapered Tubes under Oblique Impacts

Based on the validated FE modeling methods, crushing behaviors of three types of tapered tubes including the aluminum alloy tube, the steel tube and the hybrid material tube were simulated and compared. The two single-material tubes have the same dimension as the hybrid tube.

Figure 4 shows the final deformation states of the three types of tubes under impact angles of 0°, 10°, 20°, 30° and 40°, and figure 5 presents the dynamic crushing force with respect to displacement accordingly. One important observation is that load angle has a significant effect on the impact behaviors of thin-walled tubes. Previous study indicated that bending deformation of the thin-walled tubes would occur and the energy absorption capability decreases significantly when the load angle exceeds a critical value [4]. In the current case, when the load angle is less than 20°, all three tubes deform progressively and maintain a great capacity of energy absorption. The crushing force oscillates around a certain value corresponding to the asymmetric folds of the tube walls. As the load

angle reaches 30°, the two single-material tubes display the so-called 'Euler-type' bending failure mode (figure 4) in association with the slump of crushing force (figure 5). In contrast, the TTWT keeps the progressive deformation up to a load angle of 40°, showing a much better energy absorption capability than the single-material tubes under oblique impact loads.

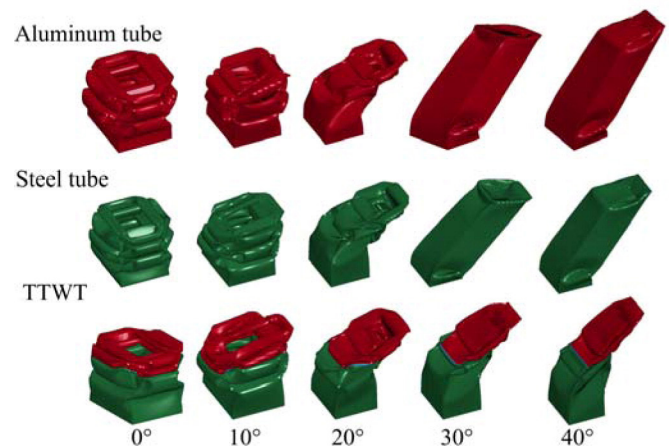
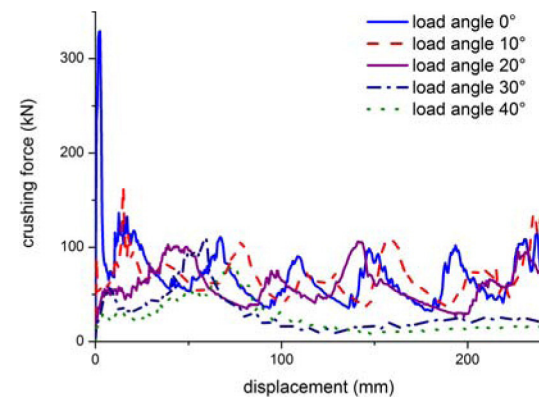
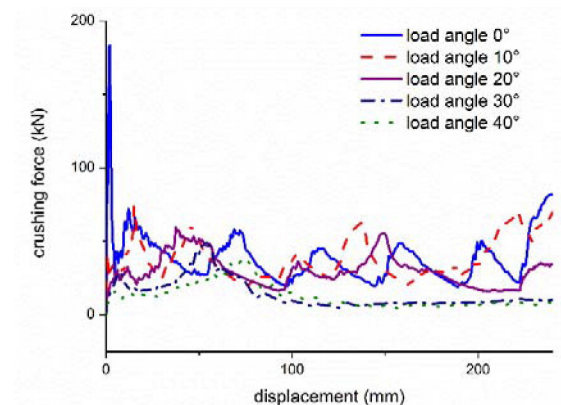


Figure 4. Final deformation of thin-walled structures of single material or dissimilar materials under oblique impacts with different angles.



a.



b.

Figure 5. Effect of load angle on crushing force with respect to deflection of tapered tubes: (a) Aluminum tubes, (b) Steel tubes and (c) TTWTs