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Dynamic crush behavior of adhesive-bonded aluminum tubular structure—Experiment and numerical simulation

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ABSTRACT

Two kinds of tubular structures were axially compressed under impact condition, where type-A structure consisted of hat shaped part and flat plate and type-B consisted of two similar hat parts. They were constructed with adhesive. Sheet materials were A1050 and A5052. The crush strength was greater in type-B. Separation of bonded flange was almost suppressed in A1050 type-A and -B structures, though it was highly visible for A5052 structure, especially in type-A. Predicted deformation behavior with separation behavior of the bonded flange by finite element method well agreed with the corresponding experimental result.

1. Introduction

It has been a very important issue to decrease the damage of the occupants in transportation, e.g. automobiles, trains. In the present day, variously shaped tubular parts in the car body play not only the role of strengthening members but also another important role of the shock absorber of the kinetic energy at collision. Automobile body engineers elaborate the body design, so that the plastic deformation takes place in an appropriate manner at collision, by which the excessive shock or acceleration transferred to the occupants is reduced. When the progressive plastic buckling lobes are orderly generated at collision, good crushing performance would be established.

The plastic buckling lobes formed in collapse deformation of thin-walled circular or square tubes, frusta, struts, honeycombs, etc. were reviewed [1]. Crushing mechanics of thin-walled components was theoretically investigated in view of energy absorber, where the analysis method based on the superfolding element concept was presented [2]. Collapse deformation of tubular structure is sensitive for tubular shape, dimensions and supporting condition, etc. Axial compression behavior of circular and square steel tubes was predicted by approximate theoretical method [3].

Further, transition from axisymmetric to non-axisymmetric mode in collapse deformation of round tube was also studied, where the wall thickness distribution, end conditions were varied [4]. Axial crush behavior for various polygonal tubes of aluminum alloy was also examined, the crush strength exhibits to saturate as the number of corners in cross-section increases [5]. Also in aerospace field, the axial collapse of tube is an important issue. The collapse with triggered device was examined in order to apply the phenomenon to the shock absorbing landing gear part [6]. Numerical simulations of top-hat thin-walled sections of dual-phase steel DP800 subjected to axial crushing was performed taking into account process history and measured geometric imperfections, thickness variations and material variations [7].

The tubular structures often consist of several parts. There are various joining methods in assembling parts. Resistance spot welding is typically used for joining steel sheet parts. The validity of analytical approach for the axial progressive collapse of welded hat and square structures was inspected, which was relied on a yield hinge model [8]. Axial collapse behavior triggered by V-shaped dent was investigated for various cross-sectional steel tubular structures. Spot welding was considered in the numerical model, where the nodes of welded portions in both parts were kept to stick on each other. The predicted collapse pattern and crush strength were in good agreement with the corresponding experimental result [9].

With respect to the alternative assembling methods, bolt joint and adhesives are also effective. Dynamic bending was performed using beam structures built up of aluminum alloy shells and steel plates, in which screw and nut fastening, adhesive joining, and their combined assembling methods were tested [10]. Spot welding and/or adhesive joining methods were applied to assembly of the steel energy absorbing hollow members with hat cross-section. Collapse mode was undesirable when adhesive was used alone [11]. For the volume production of aluminum spaceframe body structures, the potential of joining techniques, solid and liquid-state welding, adhesive bonding and mechanical fasteners

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were considered. It concluded that combination of these techniques could answer [12,13].

Axial crush behavior of square box columns was experimentally investigated using adhesives and the laser-welding. The energy absorption performance of continuously joined structures are equivalent or better than that of spot-welded structures [14]. Crushing of double hat cross-sectional members fabricated with adhesive, self-piercing rivet was experimentally studied using aluminum and steel sheets. The absorbed energy of tubular structure using self-piercing rivet was slightly higher than that using adhesive [15]. The buckling load or the initial peak stress, and the buckling mode were examined considering the difference in flange stiffening between the adhesively bonded and unbonded aluminum hat sections. Finite element eigenvalue buckling analysis was also carried, where the adhesive material was modeled by a group of linear springs. However, progressive plastic buckling was not considered [16].

For modeling aluminum hexagonal honeycomb, a numerical model of double wall portion including adhesive layer between the walls were proposed. The effectiveness of the model was demonstrated [17]. Experiment and numerical study were carried out for aluminum and aramid paper honeycombs. Several numerical techniques for modeling honeycomb core were developed [18]. Further, theoretical approach to estimate the mean crushing stress and wavelength of folding lobes was also carried out. The calculated results were well agreed with the experimental result, though the deformation of adhesive was neglected due to that the strength is weak [19]. However, the progressive collapse behavior of the aluminum tubular structure with hat-shaped cross-section has not been almost investigated. It may be due to that the assembly by spot welding and other reasonable welding methods are practically difficult.

In this paper, straight aluminum tubular structures with two kinds of cross-sections were axially compressed under the dynamic or quasi-static condition. The structures were assembled with epoxide adhesive, where hat shaped part and flat sheet or twinned hat-shaped parts are bonded at flange portion. The objectives are to investigate the effect of the tubular cross-section and the deformation behavior of the bonded flange portion on the general collapse behavior. The impact velocity was 10 m/s under dynamic condition, where a drop-hammer testing apparatus was used. Pure aluminum A1050 and an aluminum alloy A5052 sheets with 1 mm thickness were used.

It is worthy to check whether the collapse deformation of adhesively bonded structure can be numerically simulated and the crushing stress can be predicted. Finite element simulation was carried out using a dynamic explicit solver DYNA3D [20]. Further, computations with several variations in the mechanical property of the adhesive were also conducted in order to examine its effect on the deformation behavior.

2. Tested tubular structures and experimental conditions

The variations of tested tubular structures are type-A and -B as illustrated in Fig. 1. The type-A structure is a straight tube with hat-shaped cross-section, composed of a hat part and a flat plate. The type-B structure is also a straight tube with twinned hat cross-section, where two similar hat parts are joined. The hat part was formed by V-bending operation with 3 mm inner bent radius as shown in Fig. 2 using the hydraulic universal testing machine. For assembling the structure, a thermosetting epoxide resin adhesive (Iida industry, OROTEX 4901) was applied at flange portion, whose shear bonding strength is about 27 MPa. The thickness of the adhesive layer was 0.3 mm. No surface treatment for the bonding interface was performed except for degreasing.

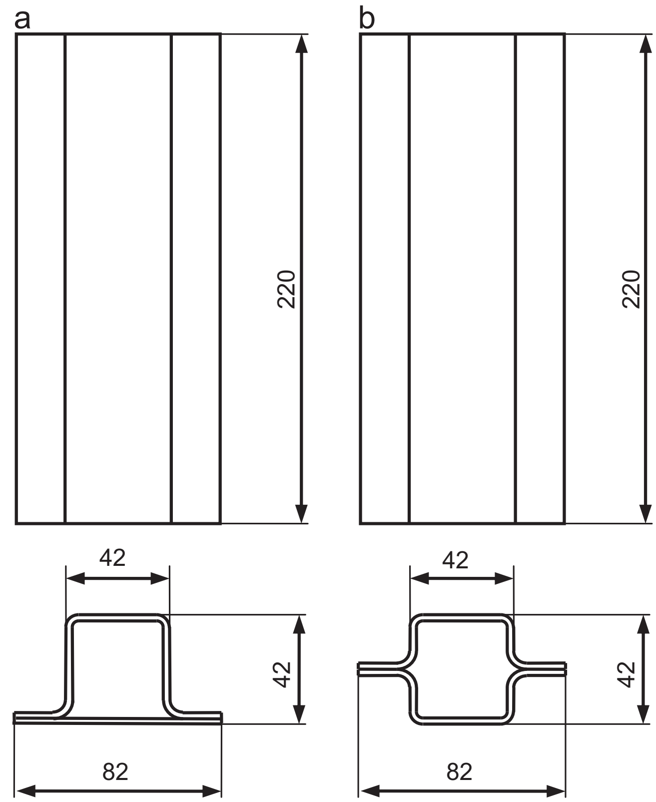

Fig. 1. Schematic of types-A and -B tubular structures (Inner corner radius: 3 mm). (a) Type-A: Hat part+flat plate and (b) Type-B: Twinned hat parts.

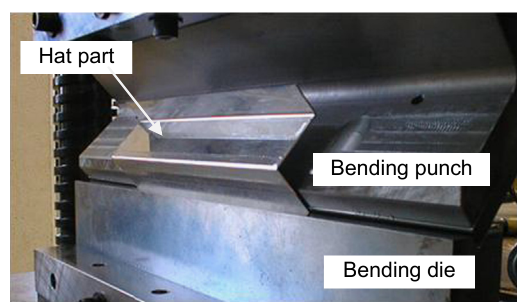

Fig. 2. Press V-bending of hat part.

Table 1
Mechanical properties of sheet materials.

Material	C (MPa)	n	U.T.S. (MPa)	E (%)
A1050-H24	149.7	0.023	132	1.5
A5052-H34	399.1	0.148	248	8.3

Plastic property: $\sigma = C\varepsilon^n$, U.T.S.: Ultimate tensile strength, E: Total elongation.

The sheet materials used were a pure aluminum A1050-H24 and an aluminum alloy A5052-H34. Their nominal thickness is 1 mm. The mechanical properties of the sheet obtained under the quasi-static condition are listed in Table 1. The drop-hammer type impact testing machine was used in impact test, on the other hand, a hydraulic type universal testing machine was used for quasi-static test. The general view of impact testing apparatus and the testing part are shown in Fig. 3. The impact velocity is set to 10 m/s. The mass of the drop-hammer is 29 kg.

The type-A structure is attached to the drop-hammer, which is impacted to the stationary plate. The type-B structure is put on the stationary plate and the drop-hammer runs into its top edge. The