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Steel spot-welded hat sections with perforations subjected to large deformation pure bending

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ABSTRACT

Steel spot-welded hat-type sections are used extensively in the automotive industry to manufacture vehicle structures. The main objective when designing a crashworthy vehicle is to protect the occupants in the event of a collision by dissipating crash energy via large plastic deformation and ensuring the survival space is not encroached. In rollover crashes, the components in the roof structure will be subjected to large deformation bending as the roof frame collapses and kinetic energy is dissipated. This paper presents a procedure whereby the energy absorbed by a spot-welded hat section under large deformation bending may be determined. The results are shown to compare well with experiments of spot-welded hat sections with seven different geometries and four different perforation sizes. The perforations were introduced into the compression flange of the sections. The range of section and perforation geometries investigated was designed to cover the full range typical to the automotive industry. The theoretical large deformation bending moment–rotation curves and energy absorbed are determined from a rigorous yet relatively simple three stage process, which includes elastic, in-plane plastic and plastic collapse mechanism components.

1. Introduction

Thin-walled steel spot-welded hat sections are a generic form of the types of steel profiles used in vehicle structures. Such structures are usually designed to provide protection to occupants when subjected to crash impact loads. In a recent investigation of vehicle rollover crashes [1,2], it was determined that the vehicle's roof structure may collapse in various mechanism forms including the side-sway mechanism more commonly identified by structural engineers in the case of unbraced pinned frames [3]. Such collapses may result in significant intrusions of the roof structure into the survival space of the vehicle, causing injury [1–8]. The collapse mechanism involves the formation of plastic hinges in the components of the roof structure, namely the pillars and the roof rails.

During routine inspections of vehicle roofs [9], it was found that the pillars and side header rails had numerous perforations or holes. An example of a roof structure, with its interior liner stripped, is shown in Fig. 1. It is obvious to thin-walled structure researchers that such perforations or holes can precipitate premature buckling and plastic hinge formation, thus reducing the overall strength and energy dissipation capacity of a vehicle's roof. This has also been pointed out by Chirwa et al. [4]. However, the effects such perforations have in terms of strength and energy dissipation capacity to side rails and pillars subjected to bending has not been quantified. To understand how such perforations reduce bending strength and energy dissipation of vehicle pillars and rails undergoing bending, the large deformation behaviour of exemplar thin-walled hat profiles representative of such pillar and rail profiles, where plastic hinge mechanisms are made to form, were studied.

This paper presents an experimental investigation of spot-welded hat section beams with and without perforations subjected to large deformation pure bending. An analytical procedure is developed to determine each beam's bending moment–rotation deformation behaviour, peak bending moment and energy absorbing capacity. The beam profiles selected represent the more common profiles found in Australian fleet vehicle roof and pillar structures. Tan et al. [9] identified the vehicle profile material thickness generally ranges from 0.8 to 1.2 mm, and width to thickness ratios are generally in the range 25–100, though can be up to 200. A similar range was found by Sironic and Grzebieta in their investigation [10]. It was also noted in the investigation that many profiles have large perforations, which typically varied between 10% and 60% of the element width.

A range of width to thickness ratios between 20 and 100 of spot-welded hat profile beams made from 1-mm-thick plate

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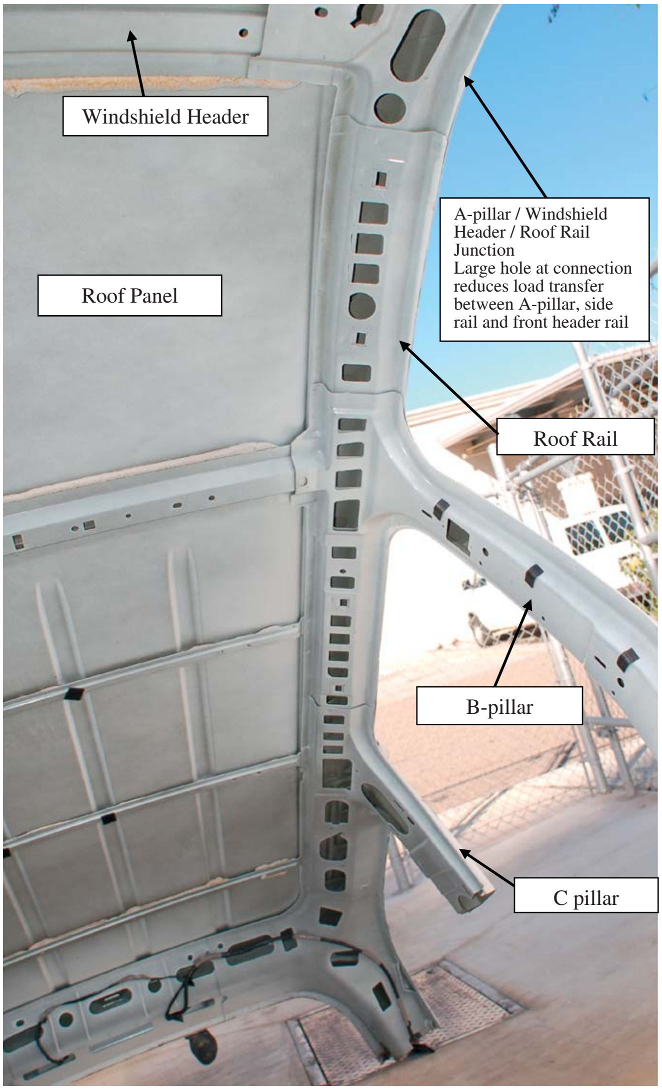

Fig. 1. Spot-welded and glued roof from a US manufactured sports utility vehicle (SUV) showing large perforations in the thin-walled pillar and side rail hat section members.

sections with perforations ranging between 0% and 60%, were subjected to pure bending tests. Standard principles of elastic bending and in-plane plasticity used in steel specifications [3,11–13] can be applied to what are commonly referred by structural engineers as non-compact and compact sections. Compact sections are also sometimes referred to as thick-walled stocky profiles. For slender thin-walled sections a plastic mechanism analysis must be employed. This same procedure can be applied to a broad range of profiles typical to vehicle structures, to determine their large deformation bending moment–rotation behaviour, peak bending moment and energy absorption capacity.

With regards to plastic mechanism behaviour, it has been well understood for over two decades that for thin-walled steel members under increasing load, localisation of the buckling pattern occurs and the post-buckling behaviour is characterised by large local displacements in the inelastic range as explained by Sironic and Grzebieta [10], Murray and Khoo [12] and Murray [3,13]. This results in plastic folding of the cross-section walls into a spatial plastic mechanism. In analysing thin-walled steel members, a generalised spatial mechanism analysis, which takes into account second-order effects, will provide a bending moment–rotation relationship from which estimates of beam and pillar strengths and energy dissipation capacity can be estimated [10,14].

The first step of such a procedure is to correctly identify the spatial plastic mechanism that forms in the member, for which experimental observations have been found to be the most reliable method. In practice, it has been observed that there are two major classes of spatial plastic mechanisms that form in steel members, namely true mechanisms and quasi-mechanisms. A true mechanism is one whereby the component plates of the cross-section fold along the plastic hinge lines, whereas in a quasi-mechanism certain zones of the plates must deform in-plane in order for the plastic mechanism to develop, resulting in yield zones in addition to yield lines.

Having established the spatial plastic mechanism, the analysis follows either an energy or an equilibrium approach. The energy method derives the equilibrium condition by equating the work of external loads to the work dissipated by the mechanism during a kinematically admissible displacement, and may be applied to stationary or rolling yield lines. The equilibrium method derives the equilibrium condition from consideration of equilibrium in infinitesimal width arbitrary strips parallel to the direction of thrust, and may only be applied to stationary yield lines.

Much research effort has occurred since the early work of Murray [12,13] to determine and analyse the spatial plastic mechanisms that form in steel members and connections, such as plates, stiffened plates, open sections (I-sections, plain channel sections, lipped channel sections and Z-sections), closed sections (square, rectangular, triangular, trapezoidal, circular, hat, double skinned squares, ring-stiffened cylinders, conical shells, and foam-, timber- and concrete-filled box sections), connections (plate to closed section connections, closed section T, X and K connections) and ductility and energy absorption studies (closed sections, foam filled closed sections). It is not the purpose of this paper to review this work but instead to refer the interested reader to the extensive review of Zhao [15] which describes and references 89 papers published in the field.

This paper presents a plastic mechanism analysis developed for steel spot-welded hat sections, with and without perforations, subjected to pure bending. A number of authors have provided plastic mechanism solutions for square and rectangular steel hollow sections [16–18]. A notable solution was presented by Kecman [18], where the results of plastic mechanism analyses were shown to compare well with experiments of 56 sections in pure bending. Grzebieta et al. [19] and Kilner [20] provided modifications of Kecman's equations for spot-welded hat section profiles. The general solution provided by Kecman is adapted for the analysis of hat sections investigated and presented in this paper, where yield lines are additionally included for the lips. For the perforated sections, appropriate modifications are introduced to account for the reduction in the length of the yield lines through the perforated element. The method is used in conjunction with elastic and in-plane plastic theory to fully describe the large deformation bending moment–rotation behaviour of a broad range of hat sections, and is shown to compare well with the experimental results.

2. Test specimens and setup

The experimental program involved 24 tests of steel spot-welded square hat sections subjected to large deformation pure bending. The hat section widths (a) and depths (b) were nominally 20, 25, 30, 40, 50, 80 and 100 mm, with lips (a_{lip}) nominally 15 mm. All sections were cold-formed from nominally 1 mm thick (t) mild steel and spot-welded every 20 mm along the length (Fig. 2). The slenderness (λ) values of the unperforated specimens,