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Lateral-torsional buckling of laterally unsupported single angle sections loaded along geometric axis

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ABSTRACT

Equal-leg single angle section (SAS) members were analyzed for flexural loading patterns along the geometric axis. Uniform, triangular, double-curvature and parabolic bending moment were produced using loading patterns over the span of member. Variations in orientation as well as in local and global slenderness ratio were considered to plot normalized moment rotation curves. Both material and geometrical nonlinearities with imperfections in member were also incorporated. These curves were compared with the existing provisions of AISC specification to verify the validity of the upper limit on C_b, which accounts for the effect of loading patterns on the elastic critical buckling moment of SAS members. Design specifications of Indian Standard (IS 800: 2007) for lateral-torsional buckling (LTB) of doubly and mono-symmetric sections were used to develop the design guidelines for limit state of LTB of SAS members. Moment capacity curves from proposed guidelines were compared with the AISC specification and were found to be safe and conservtive.

1. Introduction

Single angle section (SAS) member is the first structural shape produced and is commonly used as a traditional structural member. It is preferred by construction engineers as its two perpendicular legs provide a better way of connection with other load carrying members and an easy platform for loading. Its compactness, lightness in weight and economic transportation is also favored by the construction industries. However, SAS member is found to be a difficult proposition from analysis point of view, as it is difficult to apply force and moment on its centroid, which lies outside the section. Shear center and the centroid do not coincide; hence, force applied to any point other than the shear center produces an additional moment about the shear center. In general, loading is applied on a leg of the SAS member which is also described as the flexural loading along its geometrical axis. AISC specification [2] provides design guidelines for SAS beam for flexural loading about principal and geometrical axis. The effects of different loading patterns and direction of load are also considered in these guidelines. However, an unsubstantiated limit on the coefficient C_b, which takes care of the variation in the loading pattern, was found and the results of the finite element (FE) study were used to validate the limit.

Limit state of lateral-torsional buckling of SAS members is not well encountered by the specifications of Indian steel design code IS 800: 2007 [3]. Existing specifications for mono and doubly-symmetric sections adopts Perry-Robertson's approach to account for the effects of imperfections in the members. Therefore, the current study was used to develop the design guidelines for SAS members bending about its geometrical axis. In these guidelines, the existing coefficients C_b (as per AISC specification [2]) and c_1 (as per [3]) were used to incorporate the variation in bending moment diagrams (BMD) over the span of the members.

2. Finite element modeling

SAS members are generally loaded along its geometrical axis. Out of many flexural loading orientations, four orientations are important for analysis as shown in Fig. 2–1. In both case 1 and case 2, SAS member is loaded such that bending moment is acting about the minor axis of the section. In case 1, the shear center, S, is in flexural tension while in case 2, it is in flexural compression. For case 3 and case 4, SAS member is loaded along the geometric axis of the sections in a way that for case 3, the shear center is in flexural compression whereas in case 4, it is in flexural tension. Case 3 and case 4 are favorable orientations from fabrication as well as loading point of view, therefore, case 3 and case 4 were considered for further study.

SAS members with varying sectional and member dimensions were considered for analysis. Local slenderness ratio (b/t) was varied from 8 to 15 and global slenderness ratio (L/r) was varied from 25 to 400. Flexural loading patterns were also varied to have four types of BMDs along the span of SAS member. Thus, including case 3 and case 4, a total

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Notation

α_{LT}	Imperfection factor
b	Width of equal-leg single angle section member
C_b	Coefficient to account the variation in the loading pattern
c_1	Factor depending upon the loading and end restraint conditions
E	Modulus of elasticity
f_{bd}	Design compressive stress
L	Span length of steel SAS beam segment
λ_{LT}	Non-dimensional slenderness ratio
M_{ob}	Elastic critical lateral-torsional buckling moment
M_d	Design moment capacity of member
M_{rd}	Redefined design moment capacity of member
r	Radius of gyration about the geometrical axis of the section
S	Shear center
t	Thickness of equal-leg single angle section member
χ_{LT}	Compressive stress reduction factor
Z_e, Z_p	Elastic and plastic section modulus, respectively

number of 168 analyses were performed to understand the behaviour of SAS members.

2.1. Naming convention

A nomenclature to analyses was adopted so that they could be distinguished by its name only. The name of the analyses was composed of four variables and represented as; $\Psi\eta\_\xi\_\lambda$, where Ψ represents loading pattern (i.e. variation in BMD), η represents member orientation, ξ represents global slenderness ratio (L/r) and λ represents local slenderness ratio (b/t). Values assigned to these variables are mentioned in Table 2–1. Similarly, a group of analyses was represented as $\Psi\eta$. For example, *U3*, which represents a group of analyses (with all L/r and b/t ratios) subjected to uniform BMD and having an orientation corresponding to case 3.

2.2. Model set-up and discretization

Finite element program, Abaqus [1] was used as a tool to analyze the flexural behavior of SAS members. 3-dimension simulation of

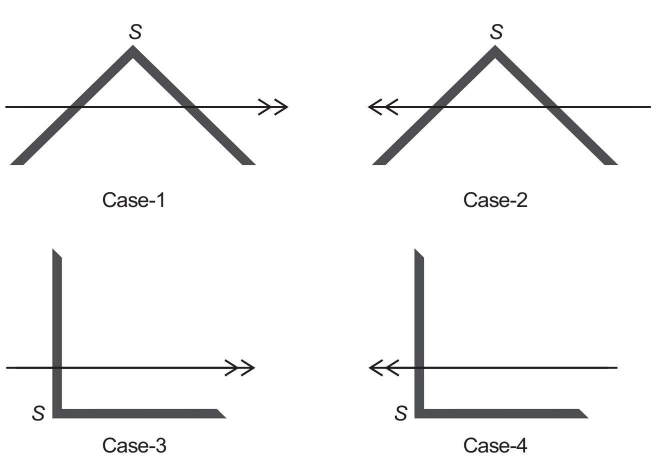

Fig. 2–1. Major loading orientations (*S* denote shear center).

Table 2–1
Representation of symbols.

Symbol	Value	Representation
Ψ	*U*	Uniform BMD
	T	Triangular BMD
	D	Double Curvature BMD
	P	Parabolic BMD
η	*3*	Downward loading direction (Case 3)
	4	Upward loading direction (Case 4)
ξ	*25, 50, …, 300, 400*	L/r = 25, 50, …, 300, 400
λ	*8, 12–5 and 15*	b/t = 8, 12.5 and 15

SAS members was done to capture both in-plane and out-of-plane behaviour. One dimension of the SAS member was too large as compared to other two dimensions; hence, 3-D shell model was considered as an appropriate option for modeling. Among the several options available for shell elements, *S9R5* of Abaqus element library was chosen which had quadratic geometric order, nine number of nodes and five degrees of freedom. Among five degrees of freedom (DOF), three were translational DOFs while two were in plane rotational DOFs. *S9R5* element was also chosen for its reduced integration technique which could minimize the effect of shear locking as well as reduce the computation time. Thin conventional shell element, *S9R5*, imposes Kirchhoff constrained numerically, i.e., shell normal will remain normal to the shell reference surface during the analysis. *S9R5* elements were also suitable for arbitrary large rotation and small strain. Geometrical non-linearity and effect of change in thickness during the analysis were also considered in the study. Centre-line modeling of SAS member was done and both material and geometric non-linearities were considered to simulate the non-linear behavior of material.

The model was divided into two major parts: two rigid beam segments and a steel beam segment as shown in Fig. 2–2. One end of each rigid SAS beam segments were connected to the ends of central steel SAS beam segment. Thus, warping was restrained at the both end of the central SAS beam segment. These rigid beam segments were also useful for the application of loads as stresss concentration due to point loads would not affect the behavior of central beam segment.

SAS members manufactured by SAIL (Steel Authority of India Ltd.) and local manufacturer were collected and fourteen coupons were prepared for the tensile testing. The tensile behavior were noted for each coupons and the average stress–strain curve was used to determine steel properties as shown in Fig. 2–3. These properties were directly assigned to central beam segment while modified properties were assigned to rigid beam segments to confirm their elastic and rigid behavior. First, the elastic part of the curve shown in Fig. 2–3 was assigned to the rigid beam segments so that plasticity would not affect behavior of the central beam, and then modulus of elasticity was made two times to ascertain their rigid behavior. Apart from these modifications in the material properties, shell thickness of these rigid beam segments was also made five times than that of the central beam segment elements. Beam segements were decretized to understand the effect of element size on the behavior of central beam segment. It was observed that variation in element size significantly affect the computational time as well as accuracy of results, therefore, a mesh convergence study was performed to obtain optimum element size.

2.3. Mesh convergence study

A study by Moen and Schafer [8] showed that a *S9R5* shell element available in Abaqus element library with aspect ratio of 8:1 or lower can be assumed to be good for the buckling analysis. Hence, elements with aspect ratio lower than 8:1 were considered for the analysis. Elements