Inelastic Cyclic Buckling of Aluminum Shear Panels

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Abstract: Cyclic load tests on shear panels of low-yield alloy of aluminum (3003-O) were performed to determine the onset and effect of inelastic web buckling on load-deformation behavior. Yielding of shear panels of aluminum can be used as a means to dissipate energy through hysteresis provided strength deterioration due to inelastic buckling is controlled. Gerard's formulation for inelastic buckling, as reported in 1948, was found to be in excellent agreement with experimental results and can be used to predict the onset of inelastic shear buckling and to design shear panels so that inelastic buckling does not occur at strains below the design requirements.

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Introduction

Shear yielding of aluminum panels can be used as a hysteretic damper to dissipate vibrational energy in many civil engineering structures, especially for earthquake resistance (Rai and Wallace 2000). However, inelastic buckling of shear panels limits energy dissipation potential of the shear panels with severe pinching of hysteresis loops. Therefore, shear panels are to be designed to avoid buckling at operating shear strains. The objective of this technical paper is to describe the inelastic cyclic behavior of the shear panels as observed on tests on medium scale (1:4) models of aluminum I beams and the development of a buckling criterion for inelastic shear buckling due to cyclic loads.

The shear web buckling criteria of the Aluminum Association (2000) are primarily those reported by Clark and Rolf (1966). Sharp and Clark (1971) summarized the observed behavior of thin aluminum shear web of plate girders under monotonic loading which formed the basis of design provisions. The limits on the slenderness ratio for inelastic buckling are functions of the yield strength and type of alloy only and are not related to shear strain levels and nature of the loading history. It has been observed that shear strength of web panels is significantly reduced for cyclic loads when large buckle waves or folds (i.e., out-of-plane web deformations) are present. Further, these buckle waves are difficult to avoid for thin webs in shear even at working loads (Sharp 1993) and significantly influence their buckling behavior. In this preliminary study, Gerard's approach (1948) is used for the inelastic buckling criterion which can be explicitly expressed in terms of applied cyclic shear strain, in order to use with deformation-based design procedures.

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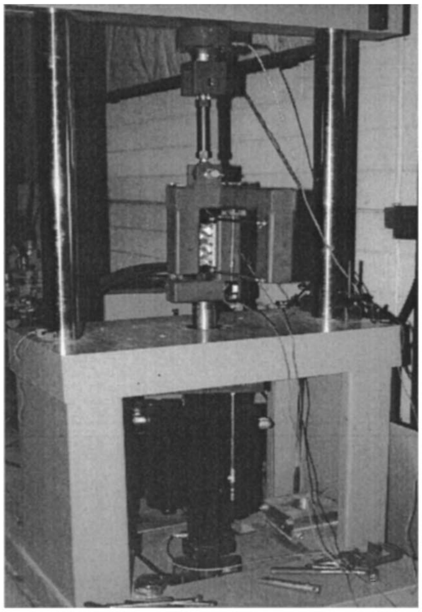
Experimental Program

Test Setup and Specimens

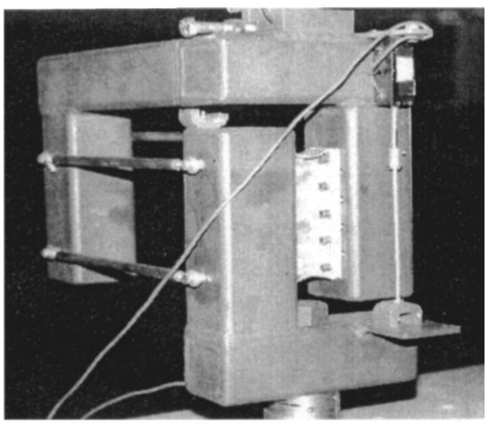
A testing system was designed as shown in Fig. 1, in which the servohydraulic actuator applied cyclic shear load to the shear panel specimen through a pair of rigid L-shaped fixtures which moved up and down with the actuator. The specimen was securely bolted to in-plane vertical legs of the top and bottom fixtures. The second vertical leg of the top fixture was laterally braced to the vertical leg of the bottom fixture to ensure the stability of the system and to prevent out-of-plane bending and twisting of the test specimen. A medium scale of 1:4 was chosen as the best compromise between specimen manufacturing ease and the available test equipment for a prototype section equivalent to W8 $\times$13 steel section of AISC (1994) to be used as a typical shear-yielding seismic energy dissipator in a steel braced frame (Rai and Wallace 2000). This scale resulted in I-shaped specimens approximately 51.6-mm deep with the clear depth and thickness of the web being 45.2 and 1.6 mm, respectively, whereas their length of 152.4 mm was governed by limitations of the loading apparatus. Transverse stiffeners of thickness 3.2 mm (same as the flange thickness) were provided at the ends of the panel to delay the initiation of plastic web buckling and to improve the postbuckling behavior of the panels. The end stiffeners were groove welded to both flanges as well as to the web.

Aluminum alloy 3003 was used for the shear panels which has manganese as its main alloying element to attain a moderate increase in strength over pure aluminum without seriously affecting its excellent ductility. Reference material properties of alloy were obtained from uniaxial tension coupon tests as follows: 0.2% offset yield stress $\sigma_{0.2}=35.2$ MPa, tensile strength$=109.2$ MPa, ultimate strain$=0.24$ and Young's modulus$=62$ GPa (Rai 1992).

The small scale wide flanged I-section test specimens were manufactured using a method developed by Rajendran (1990). This method consisted of making an I section from five strips (two separate strips for each of the flanges and one strip for the web) and tungsten inert gas (TIG) welding the flange and web strips from the outside of the flange. The heat caused by welding removes the effect of the thermal treatment provided to the aluminum alloy especially in and around welded regions. This results



(a)



(b)

Fig. 1. (a) Details of test fixture and (b) close-up view of specimen inside fixture

in a distribution of strength which varies along the cross section of the profile, with the minimum at the weld equal to the elastic limit of the annealed material. The entire specimen was annealed and hence, relieved from residual stresses before the test, by heating to and holding at a temperature of 413°C for two hours before being allowed to cool slowly at a rate of 28°C per hour in the heat treating oven.

Loading History

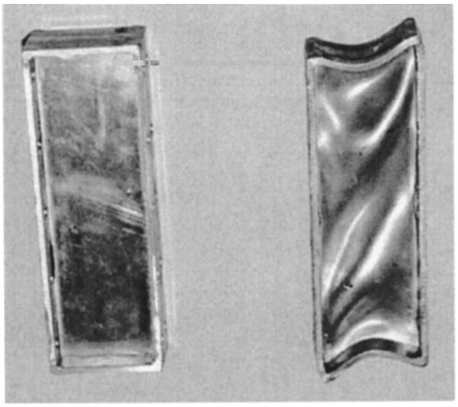
Specimens were subjected to reverse cycles of equal amplitude during both the stress and strain controlled regimes of the testing program. The choice of loading history was guided by the primary objective to obtain the basic cyclic (hysteretic) behavior of shear panels to large amounts of shear strains, which will further permit the evaluation of cyclic softening, strength, and stiffness deterioration and energy dissipation characteristics for seismic applications besides facilitating mathematical modeling and consistent comparison of test results (ATC 1992). For quasistatic tests, a typical loading program began with three cycles at 8.3 MPa of web shear stress below yield in the elastic regime, then three cycles at 20.7 MPa, which was near the expected yield stress of the web material. At this stage, the experiment was switched to the strain controlled mode and groups of three cycles were performed at shear strain levels of 0.002, 0.005, 0.02, 0.05, 0.1, 0.2 (mm/mm), etc. until specimen failure.

To understand the effect of different strain rates on the shear panel behavior, specimens were tested at three cycling frequencies—5, 10, and 17 Hz. For these specimens too, three cycles were performed at the same strain levels as for pseudostatic specimens, except for the smallest 0.002 strain cycle which was omitted due to a limitation of the experimental setup in controlling small actuator displacements at high-cycling frequency. This loading scheme resulted in a particular specimen subjected to different strain rates even for the same cycling frequency. For example, the specimen cycled at 17 Hz experienced strain rates of 0.34 and 13.6 strain/s during shear strain cycles of 0.005 and 0.2, respectively. In these tests, the shear strain rates varied from the minimum of 0.1 strain/s to the maximum of 13.6 strain/s. One specimen was tested at a frequency of 0.01 Hz, for which the strain rate varied from 8×10^{-5} to 0.008 strain/s. This was considered to be representative of a pseudostatic test, and served as a baseline for comparison.

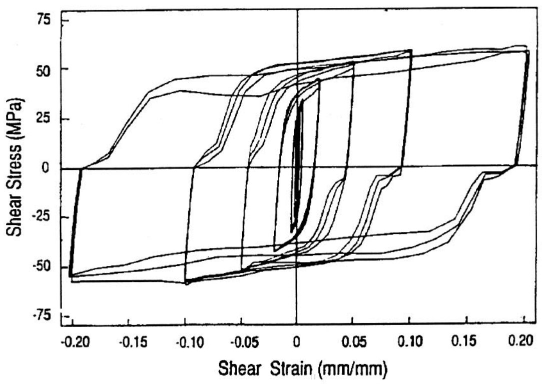
Observed Hysteretic Behavior

Fig. 2 shows a typical specimen, which was subjected to a cyclic shear loading of strains up to 0.2, and the observed shear stress-shear strain hysteretic response. The 3003-0 aluminum alloy of the panel sustained large plastic deformations without tearing. First yield was typically observed at 0.002 strain and at a stress of 0.722 times the 0.2% offset yield stress $\sigma_{0.2}$ of the material. The panel strain hardened during subsequent cyclic loading and achieved an average stress of 1.866 $\sigma_{0.2}$ in 0.2 strain cycles. Stable hysteretic loops were observed up to 0.1 strain when for the first time, web buckling was observed and degradation in strength following the Bauschinger effect was observed in 0.2 strain cycles. Severe panel buckling was observed at this stage and specimens appeared distressed with deformed stiffeners. A strength drop of about 40% of peak stress was observed following the Bauschinger effect, but most of the strength was regained at the peak strain of the cycle. Cyclical diagonal tension field developed a Pratt truss action as recognized in works on plate girders (Sharp and Clark 1971), thereby achieving stable hysteresis behavior. During the next cycles of 0.2 strain, rapid degradation of strength was observed between peak strains of cycles, decreasing with each subsequent cycle. However, the specimens regained most of the lost strength at peak strains of each cycle despite the severely distressed end stiffeners and large folds in the web at this stage.

Fig. 2(c) shows a typical shear stress-strain behavior of the specimen tested at a cycling frequency of 10 Hz which means that strain rates varied from 0.2 to 8 strain/s. Similar to slow tests, noticeable plastic web buckling was observed at 0.1 strain and the loops remained stable until this stage. Moreover, the rapid degradation of strength was observed at 0.2 strain. Similar strain hardening of the loading peaks with increasing strains were also observed. At the end of the tests, specimens tested at faster strain rates experienced relatively large out-of-plane displacement (folds or buckle waves) and suffered severe to moderate tearing of the web along the flanges.



(a)



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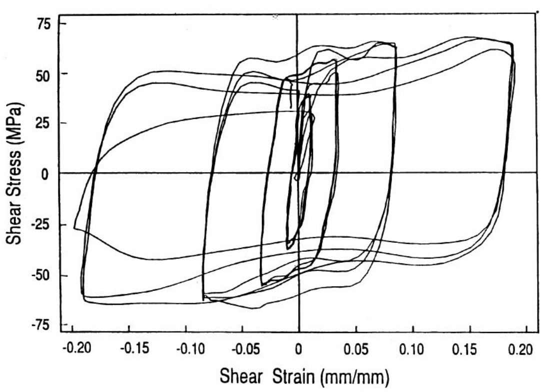

(c)

Fig. 2. (a) Typical test specimen before and after test, (b) typical hysteretic response of specimen tested quasistatically, and (c) typical hysteretic response of a specimen tested at cycling frequency of 10 Hz

Cyclic Web Buckling and Stiffener Spacing

The cyclic test of shear panels demonstrated that specimens avoided the elastic web buckling problem as expected. However, plastic web buckling was observed in all specimens at cycles of 0.1 strain, which is associated with significantly less reduction in energy dissipation capacity than the specimen without end stiffeners as shown in Fig. 3. This reduction in energy dissipation was achieved by delaying inelastic web buckling and supporting the tension diagonal of the Pratt truss by transverse web stiffeners. The solution to the plastic cyclic web buckling problem can be obtained by modifying the solutions obtained for monotonic

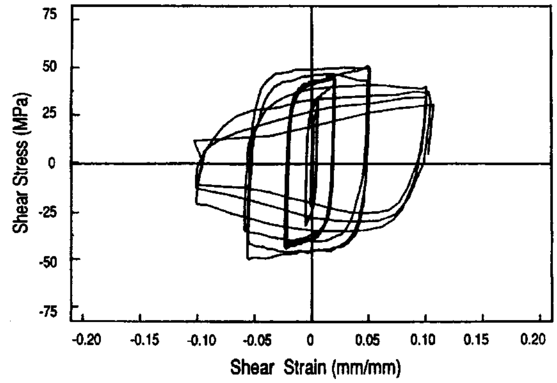

Fig. 3. Hysteretic response of specimen without end transverse stiffeners

cases, considering the similarity of the web buckling modes (Galambos 1998). The approach followed is similar to what Gerard (1948) developed for the plate problem. Additionally, the plastic web buckling problem has been formulated to be analogous to the elastic buckling problem and can be expressed as

$$\tau = \eta(\tau) \times \tau_E \tag{1}$$

where $\eta(\tau)$ = plastic-reduction factor which is related to postelastic behavior of the plate, and τ_E = elastic buckling stress given by

$$\tau_E = k_s \frac{\pi^2 E}{12(1-\nu^2)} \left(\frac{1}{\beta}\right)^2 \tag{2}$$

where E = Young's modulus; ν = Poission's ratio; β = web depth-to-thickness ratio; and k_s = buckling coefficient which depends on the aspect ratio α of the web subpanel formed by the transverse stiffeners and on its restraint conditions. α is defined as the ratio of stiffener spacing a to the clear depth of web ($d_w = d - 2t_f$), where t_f = thickness of the flange. It is reasonable to assume clamped end conditions for the web panel, as the stiffeners welded to the web and the flanges of a rolled section provide significant restraint to the web. In that case, k_s is given by (Moheit 1939)

$$k_s = \left(\begin{array}{ll} 5.6 + \dfrac{8.98}{\alpha^2} & \text{for}(\alpha \leqslant 1) \\ \\ 8.98 + \dfrac{5.6}{\alpha^2} & \text{for}(\alpha \geqslant 1) \end{array} \right) \tag{3}$$

An experimental value for the plastic reduction factor η can be obtained from Eq. (1) by substituting $\tau = \tau_b$ at the buckling stage for each of the shear panels, as shown in Table 1. Gerard proposed an empirical expression for η as a function of the ratio of shear secant modulus G_s and shear modulus G of the shear panel, i.e.,

$$\eta = f \times \frac{G_s}{G} \tag{4}$$

where f = proportionality constant and G_s is defined as

$$G_s = \frac{\tau}{\bar{\gamma}} \tag{5}$$

where $\bar{\gamma}$ is defined as shown in Fig. 4 along with the schematic showing deformed shear panel under the action of reversed cyclic loads. In all specimens, the buckling was first observed during the first excursion of 0.1 strain cycle (say γ_2 in Fig. 4) following

Table 1. Inelastic Web Buckling of Shear Links

Specimen number	Cycling frequency (Hz)	τ_b[a] (MPa)	$G_s=\tau_b/\bar{\gamma}$[b] (MPa)	G_s/G[c]	τ_b/τ_E[d]	f
1	Pseudostatic	55.1	367.3	0.0141	0.0531	3.7660
2	0.01	55.7	371.3	0.0143	0.0537	3.7552
3	5	59.9	399.3	0.0154	0.0577	3.7468
4	5	58.8	392.0	0.0146	0.0567	3.8836
5	5	57.1	380.7	0.0151	0.0550	3.6426
6	10	65.0	433.3	0.0167	0.0626	3.7485
7	10	62.8	418.7	0.0161	0.0605	3.7578
8	17	60.2	401.3	0.0154	0.0580	3.7662
9	17	63.1	420.7	0.0162	0.0608	3.7531
Average						3.7578

[a]Experimental value of inelastic web buckling stress, i.e., observed peak shear stress at 0.1 strain.

[b]$\bar{\gamma}=0.15$ (mm/mm).

[c]$G=$ Shear modulus of aluminum $=26$ GPa.

[d]$\tau_E=$ Elastic buckling stress $=1{,}038$ MPa ($a=146$ mm, $d_w=45.2$ mm, $t_w=1.6$ mm, $b=38.8$ mm, $\alpha=3.7629$, $\beta=24.25$, $k_s=9.375$, $E=70$ GPa).

cycles of 0.05 strain (say γ_1 in Fig. 4), which means that $\bar{\gamma}$ at the buckling was 0.15 (i.e., $\gamma_1+\gamma_2$, neglecting small elastic portions of total shear deformations). The values of ratio G_s/G and proportionality factor f is calculated for each specimen as shown in Table 1. Using an average value of f equal to 3.76, Eq. (4) becomes

$$\eta=3.76\times\frac{G_s}{G} \tag{6}$$

The expression for η is purely a function of strain hardening properties of the material, an observation which agrees with the study of Kasai and Popov (1986) concerning steel shear-link

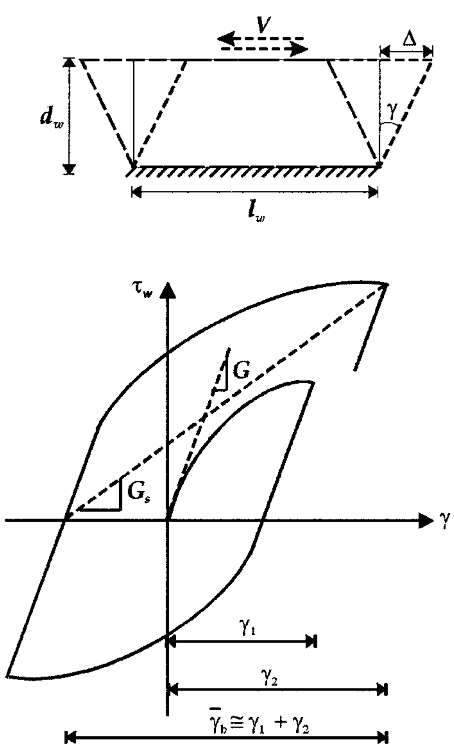

Fig. 4. Deformation of shear panel and definition of secant shear modulus, G_s and shear deformation angle, $\bar{\gamma}$ for Gerard's buckling criterion

beams of eccentrically braced frames. Substituting Eq. (6) into Eq. (1), with $\tau=\tau_b$ at the buckling stage, we obtain

$$\tau_b=3.76\times\frac{G_s}{G}\times\tau_E \tag{1'}$$

Substituting Eq. (5) with $\tau=\tau_b$ and $\bar{\gamma}=\bar{\gamma}_b$ at the inelastic buckling stage, $\bar{\gamma}_b$ can be obtained as

$$\bar{\gamma}_b=3.76\times\frac{\tau_E}{G} \tag{7}$$

Substituting Eqs. (2) and (3) in Eq. (7) and taking $\nu=0.34$, Eq. (7) can be simplified to

$$\bar{\gamma}_b=9.37\times\frac{k_s}{\beta^2} \tag{8}$$

Eq. (8) is a simple relationship connecting the web buckling deformation angle $\bar{\gamma}_b$ to the web panel aspect ratio α and the web panel depth-to-thickness ratio β. It can be used to determine the spacing of transverse stiffeners to avoid web buckling by taking $\bar{\gamma}_b$ equal to an expected peak-to-peak web deformation angle $2\gamma_d$ for fully reversed cycles of loadings as shown in Fig. 4. The estimation of γ_d is specific to applications, for example, it can be related to maximum allowable drift of the braced frame where the shear panel is used as seismic energy dissipator (Rai and Wallace 2000). It should be noted that the above relation (8) has an obvious limitation that it was developed using only one geometry for the panel (i.e., essentially one buckling load), and the relation needs to be further verified with specimens of different geometries.

Conclusions

The shear yielding of an aluminum panel is very ductile and has significant energy dissipation potential if inelastic web buckling is prevented below the shear strains of interest. Cyclic load test on I-shaped beams was used to obtain the proportionality factor in Gerard's formulation of inelastic buckling. This factor was observed to be nearly constant for all specimens and its value was determined as 3.76 for the web of the I-shaped beam which was considered clamped at all four sides. This result is further used to obtain a relation between panel aspect ratio, the web panel depth-to-thickness ratio, and web buckling deformation angle for cyclic inelastic buckling, which can be used to determine the spacing of stiffeners, which will limit the inelastic web buckling at design shear strains. The proposed relation is tentative as it is based on a very limited experimental data set and for it to be definitive the data set must be expanded by including results from specimens of different geometric proportions.

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