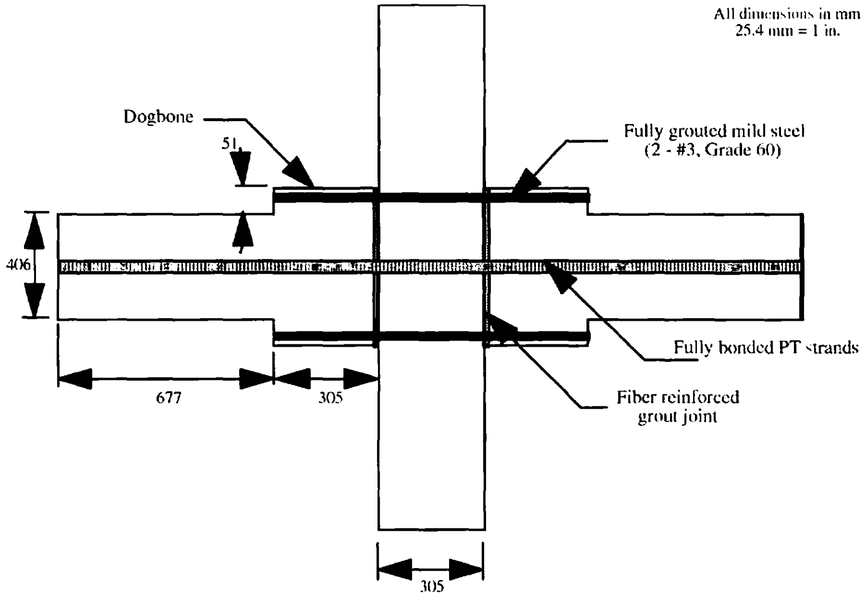


Figure 3a Specimen I-P-Z4 and K-P-Z4.

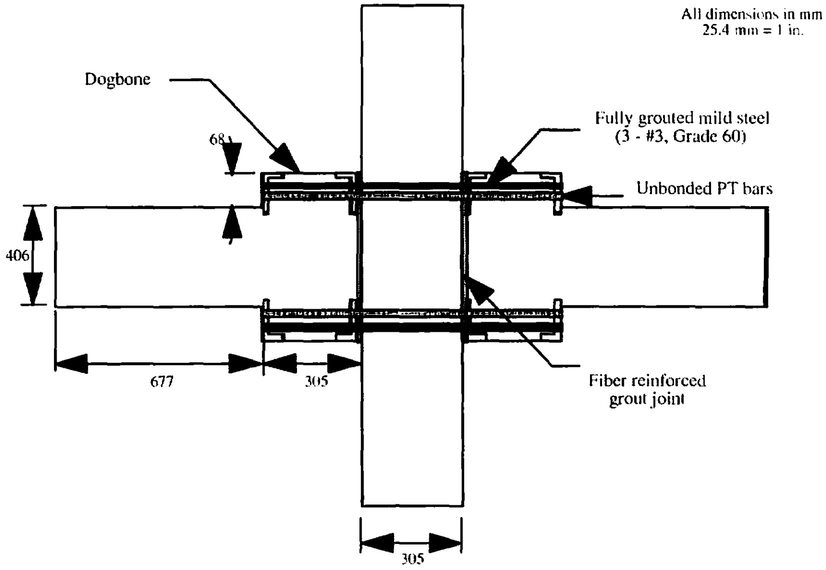


Figure 3b Specimen J-P-Z4.

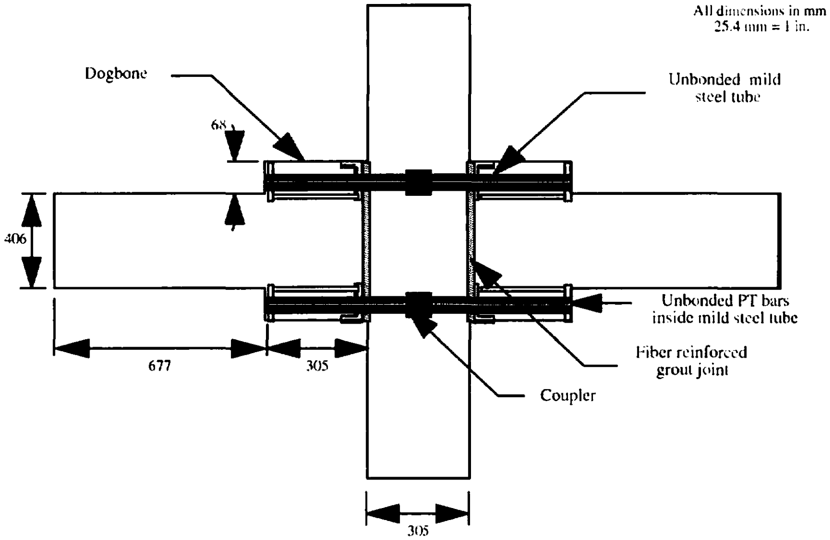


Figure 3c Specimen L-P-Z4.

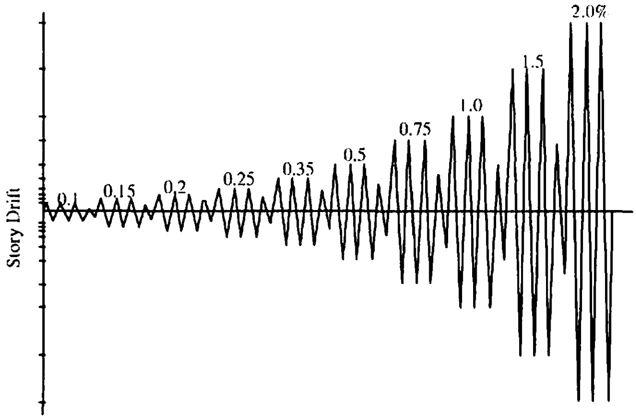


Figure 4 Drift Based Loading History.

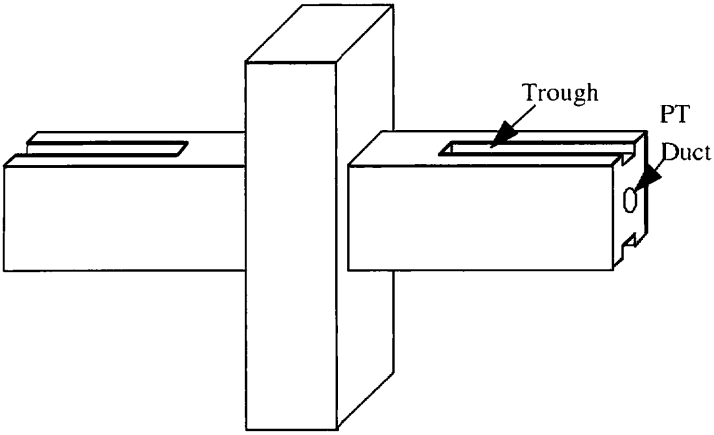
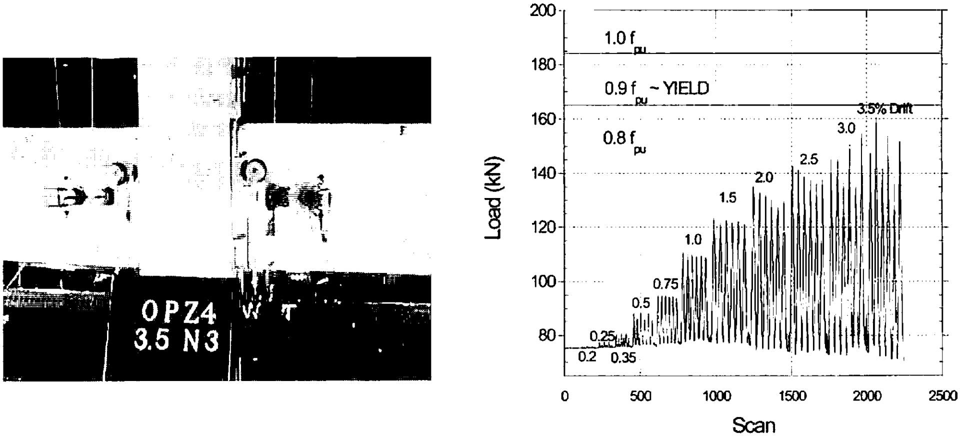


Figure 5 Phase IV B Specimens – Beams with Troughs and Central PT.



a. Specimen at Failure
3.5% Story Drift

b. Load Profile in PT Steel

Figure 6 Hybrid Specimen O-P-Z4.

SP-213—7

Shear Strength of Lightweight Concrete Beams with Stirrups Near Code Minimum

by J. A. Ramirez

Synopsis: The new ACI 318-02 provision for minimum shear reinforcement, Equation (11-13), is based on tests of normal weight concrete beams. The evaluation of experimental data supported the code change making minimum shear reinforcement a function of the concrete cylinder strength. However, it also indicated that caution should be exercised when extrapolating current code minimums to beams with concrete cylinder strengths above 13 ksi (90 MPa). Because of the paucity of data on the shear strength of higher strength lightweight concrete beams with stirrups near code minimum values, the performance of this type of member is experimentally evaluated in this paper. The program consisted of four prestressed concrete beams, two specimens contained no stirrups, and two had stirrups near the code minimum. The specimens failed at shear capacities above calculated values. In the beams without stirrups, a 44% increase of the concrete cylinder strength resulted in a 28% increase of the measured shear strength. However, in the specimens with shear reinforcement (PC6S and PC10S), a 56% increase of the concrete cylinder strength only resulted in a 3% increase of the measured shear strength. The findings from the experimental program indicate that the current code minimum stirrups for lightweight concrete beams should be re-examined. The requirement results in a lower amount of minimum stirrups for higher strength lightweight concretes in comparison to the minimum amount required for an otherwise identical normal-weight concrete beam.

Keywords: beams (supports); crack control; ductility; high-strength concrete (HSC); lightweight-aggregate concrete; minimum shear reinforcement; shear strength; stirrups

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INTRODUCTION

Structural engineers have continually tried to optimize building materials by improving their durability and effectiveness. Lightweight aggregate concrete (LWC) has been used in place of normal-weight concrete (NWC) in building applications to decrease dead load and reduce member dimensions. The reduction in dead load due to the use of LWC may permit smaller foundations and lead to cost savings. In particular, due to lower handling, transportation, and construction costs, the lightweight concrete products are ideally suited for production of precast concrete elements. The semi-empirical nature of code procedures to design for shear structural concrete beams, the known lower diagonal tensile strength of LWC, the increasing use of higher concrete compressive strengths in design, and a paucity of data on the shear strength of LWC beams with low or minimum amount of stirrups justify the evaluation of the current requirements for minimum shear reinforcement.

A usual motivation for the minimum amount of shear reinforcement in design is that the tensile strength of the concrete may be reduced because of imperfections during construction, or other similar reasons. This would then decrease the beam diagonal cracking load making the presence of stirrups necessary to provide reserve shear strength. The reserve strength would prevent a sudden shear failure on the formation of first diagonal tension cracking and enhance deformation capacity. Minimum shear reinforcement must also control the growth of diagonal cracks at service load levels. In this regard, it is also necessary to limit the maximum spacing of the stirrups representing the code minimum.

RESEARCH SIGNIFICANCE

Lightweight aggregate concrete differs from normal-weight aggregate concrete in that it results in members with a lower diagonal tensile strength, and the observed roughness of the crack face is less since cracks tend to run through the aggregate. It is also more brittle than gravel aggregate concrete in compression. The first two characteristics can be critical to the shear capacity of beams with low amounts of stirrups. The brittleness in compression indicates a need to re-evaluate the upper limit of the shear capacity as controlled by web crushing failure. This paper focuses on the shear strength of higher strength concrete beams made of sand-lightweight aggregate concrete (SLWC) with stirrup reinforcement amounts near code minimum levels. Sand-lightweight aggregate concrete refers to concrete containing lightweight coarse aggregate and normal-weight fine aggregate.

ACI 318-02 CODE MINIMUM STIRRUPS

Previous of editions of the ACI 318 have required an amount of minimum stirrups independent of the concrete strength. For beams with higher strength concretes a limitation of 100 psi (0.69 MPa) was imposed on the values of $\sqrt{f'_c}$. Larger values of $\sqrt{f'_c}$ were allowed if minimum stirrups were provided to resist a shear stress, $v_s = rf_y = (f'_c/5000)*(50)$ in psi, but no more than 150 psi (1.03 MPa). The increase in the minimum amount for beams with concrete strengths in excess of 10,000 psi (70 MPa) was deemed justified on the basis of tests of beams having concrete strengths up to 12,000 psi (83 MPa) conducted by Mphonde and Frantz (2) and Elzanaty, Nilson and Slate (3) that indicated that high cylinder strengths do not necessarily result in high values of failure shear stress in members ***without stirrups***. This was attributed to a significant reduction in the crack roughness as the concrete strength increased. This deficiency was somewhat offset by an observed ***increased efficiency*** of the stirrups compared to that calculated on the basis of Equation (11-15) in the ACI 318-02.

Since then, a number of test programs have addressed the performance in shear of reinforced normal-weight-high-strength concrete (NWHSC) beams with code minimum stirrups (5-10). The test results of beams (a/d of greater than 2.5) containing an amount of stirrups near code minimum in terms of shear stress ($v_s = rf_y = 50$ psi (0.34 MPa)), of 43 psi (0.30 MPa) $\leq rf_y \leq$ 58 psi (0.40 MPa), are shown in terms of the ratio of test to calculated ACI 318-02 shear stress (Figure 1). and in terms of the ratio of reserve shear stress to calculated shear capacity in Figure 2. The calculated shear stress is obtained using Equations (11-3). $v_c = 2\sqrt{f'_c}$ in psi, and (11-15), $v_s = rf_{yv} = (A_v/(b_w s))(f_{yv})$, in the ACI 318-02. In these expressions, f'_c = cylinder compressive strength at test date, A_v = area of shear reinforcement within a distance s, s = spacing of stirrups in a direction parallel to the longitudinal reinforcement, b_w = web width, and f_{yv} = yield strength of stirrup reinforcement. The reserve shear stress is estimated as the difference between the shear stress at failure (test shear stress), $v_{test} = V_{test}/(b_w d)$, and the calculated concrete contribution to the shear strength, v_c. d = effective depth of the member measured from the extreme flexural compression fiber to the centroid of the longitudinal tension reinforcement. In both figures, the product $100(A_s/bd)/(d^*f'_c)$ is used to illustrate the combined effect of the percentage of longitudinal tension reinforcement, the effective depth of the member, and the concrete compressive strength.

It is well known that low percentages of longitudinal tension reinforcement have a detrimental effect on the shear strength of beams without stirrups, and that increased beam depth in beams without well distributed skin reinforcement and without stirrups also has and adverse effect on the shear strength (4). Angelakos et al. (5) noted that changing the longitudinal tension reinforcement ratio from 0.5 to 2.1% increased the observed shear strengths of beams without stirrups by over 60%. The significance of well-distributed skin reinforcement, approximately 0.29%, was demonstrated by Collins and Kuchma (6) with the test of Specimen BM100D having an effective depth of 925 mm (36.4 inches), near minimum stirrups, 58 psi (0.40 MPa) similar to Specimen BM100, and concrete cylinder strength of 47 MPa (6.8 ksi). The ratio of failure to ACI calculated shear capacity increased from 0.8 to 1.1.

Figures 3 and 4 show the same ratios for safety and reserve strength graphed against concrete cylinder strength, f'_c, for the specimens with 50 psi (0.34 MPa) minimum stirrups, and with longitudinal tension reinforcement ratios less than 2.5% from Yoon et al. (10), Roller and Russell (9) and Johnson and Ramirez (7). The Angelakos et al. (5) and Collins et al. (6) specimens were removed from these comparisons because they did not meet the requirements of Sec. 10.6.7 for skin reinforcement in the ACI 318-02. The Ozcebe et al. (8) specimens were removed because the ratios of longitudinal reinforcement ranged from 2.5% to around 4.5%.

A descending trend can be observed in both figures with increasing concrete cylinder strengths. In the Roller and Russell (9) study, three out of ten specimens tested contained minimum stirrups equivalent to a 50 psi (0.34 MPa) shear stress. The three specimens are shown in Figures 1-4. Two out of these three specimens failed in shear at a strength well below the calculated using Eqs. (11-3) and (11-15) in the ACI 318-02. The unsafe beams had cylinder compressive strengths of 17.4 ksi (120 MPa) and 18.2 ksi (125 MPa). The mode of failure was defined as diagonal tension in both specimens. The third specimen failed in shear compression with a ratio of test to calculated shear capacity of 1.1. It had concrete cylinder strength of 10.5 ksi (72 MPa). The researchers noted that the first diagonal crack not initiated by a flexural crack generally occurred at a shear less than the concrete contribution calculated using the 318 provisions. They also noted that the difference between the two decreased as the amount of shear reinforcement was increased. This finding could be interpreted as the role of the stirrups in delaying the observed onset of diagonal cracking. The researchers noted, based on the findings of the study, that the ACI Code provisions overestimated the concrete contribution to the nominal shear strength when the concrete compressive strength is greater than 17 ksi (117 MPa). They further supported a recommendation from and earlier study by Johnson and Ramirez (7), making the amount of minimum stirrups a function of the concrete cylinder strength to compensate for the lack of conservatism in the estimate of the concrete contribution to the member shear strength at high-concrete compressive strength levels.

The minimum amount of shear reinforcement required for reinforced concrete beams was made a function of the concrete cylinder strength in the form a continuous function, Equation (11-13), in the ACI 318-02. Equation (11-13) provides minimum stirrups in an amount sufficient to develop a shear stress, $v_s = rf_{yv} = 0.75\sqrt{f'_c}$ (in psi) but no less than 50 psi (0.34 MPa). The step function for allowing values of $\sqrt{f'_c}$ greater than 100 psi (0.7MPa), if minimum stirrups were provided to resist a shear stress, $v_s = rf_y = (f'_c/5000)*(50)$ in psi, but no more than 150 psi (1 MPa), was then removed. Figure 5 shows the same data graphed in Figures 3 and 4, but in terms of stirrup efficiency versus concrete cylinder strength. Stirrup efficiency is defined as the ratio of the difference between the failure shear stress and the calculated concrete contribution from Eq. (11-3) to the shear capacity provided by the stirrups rf_y obtained from Eq. (11-15) in terms of stress. This figure includes the Ozcebe et al. data (8) to illustrate the beneficial effect of longitudinal reinforcement with increasing concrete strengths. Rolle and Russell (9) indicated that an increase of almost 1.3 times the previous minimum amount of 50 psi (0.34 MPa) was needed to prevent unsafe estimates, and almost 1.8 times to achieve at least 50% reserve strength over the amount estimated as the concrete contribution.

In the Rolle and Russell study, an otherwise identical beam with normal weight concrete having cylinder strength of 18.2 ksi (125 MPa), and stirrups providing a shear strength, $v_s = rf_y = 102$ psi $\approx 0.75\sqrt{18200} = 101$ psi (0.7 MPa), was tested. The specimen failed in shear compression at shear stress equal to 0.84 times the calculated value using the ACI provisions Equation (11-3) and Equation (11-15). Until more data are available, caution should be exercised in extrapolating the current provisions beyond 13 ksi (90 MPa) where stirrup efficiencies of at least 50% were observed (Figure 5).

MINIMUM STIRRUPS IN LIGHTWEIGHT CONCRETE BEAMS

Extensive experimental data (11, 12) from tests of lightweight concrete beams without stirrups indicate a reduction in the diagonal tensile strength with respect to that of beams with gravel aggregate (normal-weight) concrete. Based on the available experimental information, Sec. 11.2 requires that one of the following modifications be applied to $\sqrt{f'_c}$ throughout Chapter 11, with a few exceptions, when lightweight aggregate concrete is utilized:

- When the splitting tensile strength is specified, $\mathbf{f_{ct}}$, and concrete is proportioned in accordance with Sec. 5.2, the value of $\mathbf{f_{ct}/6.7}$ shall be used instead of $\sqrt{f'_c}$, but $\mathbf{f_{ct}/6.7} \leq \sqrt{f'_c}$.

- If $\mathbf{f_{ct}}$ is not specified, all values of $\sqrt{f'_c}$ have to be multiplied by 0.75 for all -lightweight concrete, and 0.85 for sand-lightweight concrete. Linear interpolation is permitted when partial sand replacement is used.

The minimum amount of stirrups required, in terms of shear stress, $v_{smin} = rf_y = 0.75\sqrt{f'_c}$ (psi) becomes in the cases where $\mathbf{f_{ct}}$ is not known, for all-lightweight $0.56\sqrt{f'_c}$, and for sand-lightweight concrete $0.64\sqrt{f'_c}$. In either case, the minimum amount cannot be less than 50 psi (0.34 MPa). The concrete contribution term in terms of stress, v_c, as per Eq. (11-3) is also modified accordingly, for all-lightweight concrete to $1.5\sqrt{f'_c}$, and for sand-lightweight concrete to $1.7\sqrt{f'_c}$. The reduction in the v_c term is justified on the basis of the experimental data on the diagonal tensile strength of lightweight aggregate concrete beams. However, no experimental data support the reduction in minimum stirrups particularly in higher strength concretes.

In the next section of this paper, experimental data from prestressed HSLWC beams with stirrups near code minimum values are presented to illustrate their behavior in shear. It must be noted that for prestressed concrete beams, it is allowed to calculate the minimum stirrups using Equations (11-13) or (11-14), and use the lesser of the two amounts. This is permitted because tests by Olesen, Sozen and Siess (13) of prestressed concrete beams with minimum stirrups indicated that the smaller amount of (11-13) and (11-14) was sufficient to develop ductile behavior in beams with a minimum prestressing not less than 40% of the tensile strength of the flexural reinforcement. However, in all the specimens tested in the Olesen et al. study Wabash River sand and pea gravel were used. The maximum size of the gravel was 3/8 inches (9.5 mm).

EXPERIMENTAL PROGRAM

Malone (14) tested four prestressed lightweight aggregate concrete beams in the Kettelhut Structural Engineering Laboratory of the Purdue University School of Civil Engineering. The lightweight coarse aggregate consisted of Haydite particles with a maximum aggregate size of 9.5 mm. In all girders natural sand was used as the fine aggregate. Target girder concrete compressive strengths varied from 41.4 MPa (6 ksi) to 68.9 MPa (10 ksi). The cast-in-place slab was normal-weight concrete. Hardened concrete proportions at the time of testing are shown in Table 1. Mild tensile longitudinal reinforcement consisted of Grade 60 No. 7 and No. 8 uncoated deformed steel bars. Grade 60 No. 3 uncoated deformed steel bars were used for the stirrups. The prestressing steel consisted of ½ in. special low-relaxation 7-wire prestressing strand with an ultimate strength of 270 ksi. The specimens were I-section pretensioned girders with a composite cast-in-place slab. The specimens were designed to fail in shear.

Specimen details are summarized in Table 2. The nominal dimensions and reinforcement details of typical test specimens are shown in Figures 6 and 7. The amounts of shear reinforcement (rf_y) varied from 0 to 0.92 MPa (133 psi). The minimum amount of stirrups as per Equation (11-13) for the 41.4 MPa (6 ksi) specimens is 0.34 MPa (50 psi). Equation (11-14) would be controlled by maximum spacing requirements resulting in 0.63 MPa (92 psi). For the specimens with 69 MPa (10 ksi) concrete, Equation (11-13) would result in 0.44 MPa (64 psi) minimum stirrups. Once again, Equation (11-14) would be controlled by maximum spacing limitations resulting in a minimum requirement of 0.63 MPa (92 psi). Stirrup strain gage locations are shown in Figure 7. Each specimen was tested simply supported and subjected to a single point load at midspan, as shown in Figure 8. Load cells placed underneath each support beam were used to monitor reactions. Load was applied to the specimen by a 2670 kN (600 kips) Baldwin testing machine.

TEST RESULTS AND CALCULATED CAPACITIES

The failure crack patterns are shown in Figures 9-12. In Specimen PC6N the failure crack was a web-shear crack in the north shear span that extended from the face of the support to the face of the loading plate, as shown in Figure 9. The maximum applied shear force was 353 kN (79.4 kips). Specimen PC6S prior to failure, had three web-shear cracks developed in each shear span. The failure crack extended form the face of the loading plate to the curtailment of the supplementary No. 7 longitudinal bars in the south span, as shown in Figure 10. The maximum applied shear force was 520 kN (116.9 kips). The first inclined cracks (web-shear cracks) in Specimen PC10N occurred in the north shear span at a shear of 440 (98.9 kips) and 445 kN (100 kips). The failure crack extended form the face of the support to face of the loading plate in the north shear span, as shown in Figure 11. The maximum applied shear force was 466 kN (104.8 kips). In Specimen PC10S, yielding of the stirrups T2, T7, T8, and T9 was observed prior to failure of the specimen. The first inclined cracks (web-shear cracks) occurred at a shear of 444 (99.8 kips) and 451 kN (101.4 kips). Near failure, two major web-shear cracks had developed in each shear span. The failure crack