ACI STRUCTURAL JOURNAL TECHNICAL PAPER

Title No. 112-S50

Compressive Strength of Unreinforced Struts

by Lucas Laughery and Santiago Pujol

At present, the majority of published literature claims that the compressive unit strength of a plain concrete strut loaded over its full cross section is greater than the unit strength of the same strut loaded over a reduced width. The strength reduction in the latter case is attributed to the development of internal tension resulting from lateral spreading of internal stress. This tension is thought to cause lateral splitting failure before the strut reaches its full compressive strength. The current investigation tests the hypothesis that unreinforced struts have lower compressive unit strength when loaded in uniaxial compression over a reduced width. This is done through the testing of 32 unreinforced concrete specimens and the creation and analysis of a database containing all available results to date of tests on plain concrete struts loaded in uniaxial compression. The additional testing reported herein was intended to make up for a paucity of data from large planar bottle struts (height ≥ 12 in. [305 mm]) tested alongside control prismatic struts. Of the 32 new specimens tested, 14 were loaded uniformly across their full cross section and 18 were loaded over a reduced width. In contrast to engineering consensus, analysis of the database including these new results suggests that the unit compressive strength of a planar concrete strut is independent of the ratio of its cross-sectional width to the width over which it is loaded.

Keywords: bottle struts; plain concrete; prismatic struts.

INTRODUCTION

Consider an idealized plain concrete strut loaded concentrically in compression across its full cross section (Fig. 1(a)). The applied force follows a path from the loading surface through the strut to the support surface. Neglecting friction at the boundaries, the strut is expected to be in a state of uniform stress. The magnitude of this stress is the applied load divided by the cross-sectional area, and its direction is parallel to the z-axis (Fig. 2(a)).

If the support surfaces are kept the same but the strut is widened along the x-axis, the nonprismatic strut shown in Fig. 1(b) is obtained. Internal stresses can now spread outward to fill the larger available cross section, giving rise to the characteristic bottle-shaped distribution by which the struts are commonly referred (Fig. 2(b)). As internal stresses spread outward, the stress distribution acquires a lateral component in addition to its longitudinal component. Because two components are needed to describe the state of stress (x, z), the strut can be referred to as a two-dimensional (2-D), or planar, bottle strut. Opposing lateral components of stress induce outward tensile stress in the bottle strut. As the applied load increases in magnitude, so does the magnitude of this tension. This eventually causes longitudinal cracks. The majority of engineering literature associates this longitudinal cracking with failure.

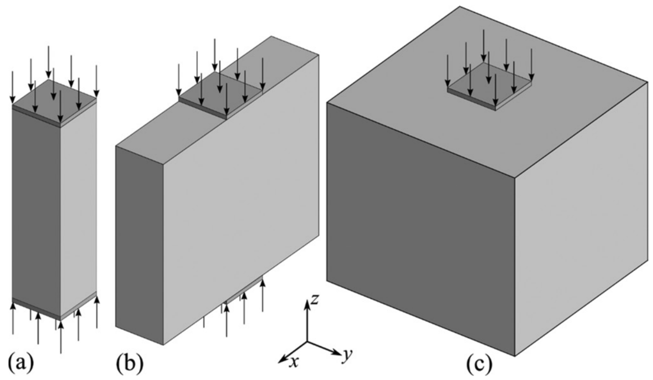

Fig. 1—Examples of: (a) rectangular prismatic strut; (b) 2-D rectangular bottle strut; and (c) 3-D rectangular bottle strut.

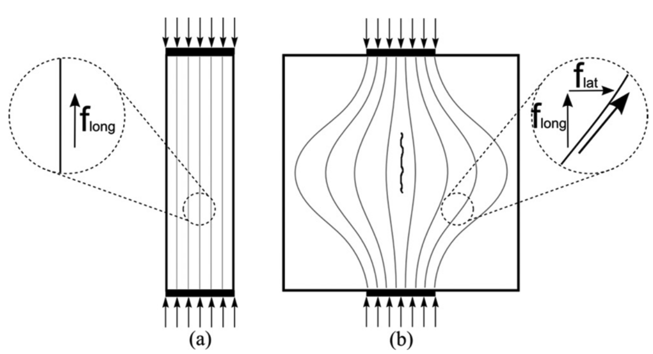

Fig. 2—Internal stresses in: (a) prismatic strut; and (b) bottle strut showing 2-D lateral dispersion.

If the strut is now extruded along the y-axis (Fig. 1(c)), the internal stress state becomes more complex. The applied axial load can now spread laterally in two directions. Because three components are required to describe the internal state of stress (x, y, z), the strut can be classified as a three-dimensional (3-D) bottle strut. Furthermore, the contribution of confinement from surrounding concrete must now be considered when evaluating the resistance of the strut to loading. From this discussion, it is clear that the internal state of stress in a bottle strut is different than in a prismatic strut. Whether this difference results in a change in strength is the current topic of investigation.

ACI Structural Journal, V. 112, No. 5, September-October 2015.
MS No. S-2014-183.R1, doi: 10.14359/51687711, received October 10, 2014, and reviewed under Institute publication policies. Pertinent discussion including author's closure, if any, will be published ten months from this journal's date if the discussion is received within four months of the paper's print publication.

Table 1—Summary of experimental strut efficiency factors from previous research

ID	Investigator and year	Shape	Stress distribution	Focus of study	Prismatic $f_b/0.85f_c'$			Bottle $f_b/0.85f_c'$			Bottle/ prismatic
					n	min.	mean	n	min.	mean	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
1	Sahoo et al. (2009a)	Rectangular	2-D	Cracking	—	—	—	14	0.59*	1.24*	—
2	Adebar and Zhou (1993)	Circular	3-D	Cracking	3	0.48*	0.59*	54	0.58*	1.27*	2.16
				Peak	6	1.11	1.19	54	1.27	2.29	1.93
3(d)	Richart and Brown (1934)	Circular	1-D	Peak	11	0.89	1.01	—	—	—	—
3(m)					12	0.56	0.84	—	—	—	—
4	Brown et al. (2006)	Rectangular	2-D	Peak	—	—	—	2	0.76	0.89	—
5	Sahoo et al. (2008)	Rectangular	2-D	Peak	—	—	—	3	1.24	1.39	—
6	Sahoo et al. (2009b)	Rectangular	2-D	Peak	2	1.00	1.00	12	0.87	1.08	1.08
7	Pujol et al. (2011)	Rectangular	2-D	Peak	12	0.93	1.14	30	0.87	1.14	1.00
Weighted averages for "2-D" specimens and peak loads:				Peak	—	0.80	1.00	—	0.89	1.13	1.13

* Value from cracking load.

Note: For each reference and strut type, the number of struts tested (n), minimum observed efficiency factor (min.), and mean efficiency factor are listed in Columns (6) through (11).

RESEARCH SIGNIFICANCE

This study compares the unit compressive strengths of unreinforced concrete prismatic struts and unreinforced concrete bottle struts. The majority of engineering literature attributes failure in bottle struts to splitting caused by transverse tension. Referring to this splitting phenomenon, engineering consensus literature assigns lower strength to unreinforced bottle struts. To date, only two published papers disagree with this consensus on the basis of direct tests of unreinforced struts (Pujol et al. 2011; Sahoo et al. 2009b). The tests and analyses presented herein likewise suggest that unreinforced bottle struts are not weaker, and are often capable of developing strength equal to prismatic struts. This finding, which is based on the analysis of a database containing all published tests to date of unreinforced struts, does not support the bulk of current engineering literature and consensus documents and, thus, merits the attention of both engineers and educators.

EXISTING RESEARCH

A brief summary of existing data from tests of unreinforced concrete specimens subjected to uniaxial compression is presented in Table 1. This table includes tests on both struts and unreinforced columns. Before the addition of the results from tests conducted in this study, specimens in the data set ranged in concrete compressive strength from 2300 to 6770 psi (15.9 to 46.7 MPa) and in aggregate size from 1/2 to 1 in. (13 to 25 mm). Results from tests of struts loaded along narrow wedges are excluded from the data. These tests were excluded because the bearing area under these end conditions approaches zero, making it difficult to normalize the test results for comparison with other results. Also excluded are tests in which one side of a specimen was supported over its full cross-sectional area while the other was loaded over a reduced area. For more details, the full database is accessible online at **https://datacenterhub.org/resources/136**.

Description of existing data

The symbols (m) and (d) in Column (1) of Table 1 denote the storage conditions of the test specimens after curing (if reported). Specimens stored in a moist room are marked (m), while those stored in dry laboratory conditions are marked (d). Column (2) identifies the author(s) and year of publication.

Column (3) refers to the cross-sectional shape of the specimens. Circular specimens were loaded through circular bearing plates, whereas rectangular specimens were loaded through rectangular bearing plates. Note that a circular prismatic strut is a cylinder tested uniformly in compression, but may have a different aspect ratio and size than a standard cylinder tested in compliance with ASTM C39.

Column (4) classifies the idealized internal stress distribution of the struts in a study as 1-D, 2-D, or 3-D (as described previously). Studies in which only prismatic struts were tested are classified as 1-D. In studies where both prismatic and bottle struts were tested, this classification is based on the internal stress distributions in the bottle struts.

Although the focus of the current investigation is peak load, some studies focused on the load at which splitting cracks formed (Sahoo et al. 2009a; Adebar and Zhou 1993). These studies are included in Table 1 for completeness and are identified in Column (5). To facilitate comparison across studies, the following equation was used to calculate an "experimental strut efficiency factor"

$$\beta_e = \frac{f_b}{0.85 f_c'} \quad (1)$$

where f_c' is reported concrete compressive strength; and f_b is the calculated unit bearing stress, obtained by dividing the reported load (either peak or cracking) by the reported bearing area. Where bearing plates had different sizes on the two loading surfaces (six cases), the smaller area was used.

Struts in these studies were divided into two types for comparison: prismatic and bottle. Because engineering literature ascribes the same unit compressive strength to all bottle struts regardless of their ratio of cross-sectional width to loaded width (as long as it exceeds 1), bottle struts of different shapes within each reference are grouped together in Table 1. For each reference and strut type, the number of struts tested (n), minimum observed efficiency factor (min.), and mean efficiency factor are listed in Columns (6) through (11). For the series in which prismatic struts were tested as control specimens, the ratio of mean bottle strut efficiency to mean prismatic strut efficiency is calculated in Column (12).

In the bottom row of Table 1, a weighted average efficiency factor for each strut type across all studies was computed using the following expression

$$\text{weighted average} = \frac{\sum_{i=1}^{m}\left(n*\beta_e\right)_i}{\sum n} \qquad (2)$$

where i refers to the i-th study; m refers to the total number of studies; n is the number of specimens in the i-th study, and the denominator is the total number of specimens for a strut type across all studies. This weighted average was calculated only for peak loads and 2-D stress distribution, which are the subject of this investigation.

Discussion of existing data

The following observations can be made from the data presented in Table 1:

1. The weighted average prismatic strut efficiency factor was 1.0, indicating that on average prismatic struts attain strengths of $0.85f_c'$.

2. For the investigation reporting both cracking and peak loads, on average, bottle struts showed peak loads over 80% higher than cracking loads (Adebar and Zhou 1993). This shows that bottle struts do not always fail with the first formation of cracks.

3. The lowest prismatic strut efficiency factor was 0.56 (Richart and Brown 1934). This demonstrates that there can be large variation in strength, even for prismatic struts.

4. For all studies that tested both prismatic struts and bottle struts, the mean ratio of bottle strut efficiency to prismatic strut efficiency (Column (12)) exceeded 1.

5. Bottle struts classified as 3-D showed higher strength than both 2-D bottle struts and prismatic struts. This can be attributed to confinement from the surrounding concrete (Adebar and Zhou 1993).

6. Improved storage conditions did not always result in higher strength. For example, specimens tested by Richart and Brown (1934) were first cured for 56 days in a moist room. Following this, specimens in Group (d) were placed in air storage for 1 year, whereas those in Group (m) were placed in moist storage for 1 year. It is not known whether specimens were dry or wet on test day, but in spite of improved storage conditions, Group 3(m) displayed lower strength than Group 3(d).

Observations 2 through 4 are inconsistent with the current accepted notion that unreinforced bottle struts fail due to transverse tension at lower compressive unit stresses than do prismatic struts. This prompted the need for more testing.

EXPERIMENTAL INVESTIGATION

The experimental investigation comprised three series of tests. Series A spanned the widest range of strut shapes, with the ratio of specimen width to loading surface width (W/B) ranging from 1 to 4. In Series B, the same concrete mixture proportions as Series A were used, but the curing time was increased. In Series C, the maximum aggregate size was doubled from 1 to 2 in. (25 to 50 mm). Specimen dimensions, curing conditions, load plate dimensions, and test results for all series are summarized in Table 2. In all tests, specimens were loaded along their full thickness (that is, their out-of-plane thickness D in Fig. 3 and 4 was equal to the dimension of the load plate in the same direction).

Series A

Series A consisted of 15 specimens of equal height and depth. Of these, six were prismatic struts and nine were bottle struts. All specimens were cast from the same batch with a maximum aggregate size of 1 in. (25 mm). Specimens were cured under moist burlap for 10 days and then were placed in air storage for either 5 or 18 days (Table 2). All specimens except Group A4 had rectangular elevations. Group A4 specimens had hexagonal elevations, with the top and bottom contact surfaces measuring 8 x 8 in. (200 x 200 mm), and midheight dimensions of 8 x 32 in. (200 x 810 mm), as shown in Fig. 3.

Series A was tested in two phases. Group A4 was tested 15 days after cast. Groups A2 and A3 were tested 28 days after cast. To provide a basis for comparison on each test day, prismatic specimens A1-1 through A1-3 were tested on Day 15, and A1-4 through A1-6 were tested on Day 28.

Series B

Series B specimens were all cast from the same batch using a mixture with a maximum aggregate size of 1 in. (25 mm). They were cured under moist burlap for 42 days and then kept in air storage for 150 days before testing. This series included prismatic struts with rectangular cross sections in addition to square cross sections.

Series C

Series C specimens were cast from the same batch using a mixture with a maximum aggregate size of 2 in. (50 mm). Specimens were cured under moist burlap for 28 days and then kept in air storage for 35 days before testing. Group C1 dimensions matched those of A1 and B1-1 through B1-3. Group C3 dimensions matched those of A3 and B3.

Testing program

Prior to testing, to provide uniform application of load, steel bearing plates were attached to each specimen using a thin layer of 10,000 psi (69 MPa) gypsum cement. These

Table 2—Summary of specimen dimensions, peak loads, and cylinder compressive strengths

No.*	Moist curing	Air storage	Specimen dimensions, D x W x H, in.	Plate width B, in.	W/B	Peak load, kip	Peak stress, f_b, psi	Group mean f_b, psi	f_c', psi	$\beta_e = f_b/0.85f_c'$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
A1-1	10 days	5 days	8 x 8 x 24	8	1	252	3940	3850	3420	1.36
A1-2						251	3930			1.35
A1-3						237	3700			1.27
A1-4		18 days				259	4040	4220	3980	1.19
A1-5						290	4530			1.34
A1-6						262	4090			1.21
A2-1			8 x 16 x 24		2	210	3280	3500		0.97
A2-2						216	3370			1.00
A2-3						247	3860			1.14
A3-1			8 x 24 x 24		3	212	3320	3780		0.98
A3-2						252	3940			1.16
A3-3						262	4090			1.21
A4-1		5 days	8 x 32 x 24		4	194	3040	3000	3420	1.05
A4-2						203	3170			1.09
A4-3						178	2780			0.96
B1-1	42 days	150 days	8 x 8 x 24	8	1	249	3890	3850	4300	1.06
B1-2						239	3730			1.02
B1-3						251	3920			1.07
B3-1			8 x 24 x 24		3	242	3780	3830		1.03
B3-2						239	3730			1.02
B3-3						255	3980			1.09
B1-4			8 x 6 x 12	6	1	174	3630	3680	4310	1.02
B1-5						183	3820			1.05
B1-6						172	3580			0.94
B2-1			8 x 12 x 12		2	197	4100	3970		1.15
B2-2						192	4010			1.10
B2-3						183	3810			1.00
C1-1	28 days	35 days	8 x 8 x 24	8	1	303	4740	4750	4870	1.14
C1-2						304	4760			1.15
C3-1			8 x 24 x 24		3	266	4160	4230		1.00
C3-2						272	4250			1.03
C3-3						274	4290		4960	1.02

* B2-3 refers to third Series B specimen with specimen-to-plate width ratio (W/B) of 2.

Notes: 1 in. = 25.4 mm; 1 kip = 4.448 kN; 1 psi = 0.006895 MPa

bearing plates were placed along the centerlines of each specimen on the top and bottom, as shown in Fig. 3. Concrete cylinder compressive strength f_c' was established on test day by testing three to five 6 x 12 in. (150 x 300 mm) cylinders in accordance with ASTM C39. These cylinder tests were conducted using a 600 kip (2670 kN) compression testing machine.

Two different setups were used to test specimens. Those specimens with a height of 12 in. (300 mm) were tested in the aforementioned compression machine under a monotonically increasing axial load. Specimens with a height of 24 in. (610 mm) were tested in a load frame consisting of a built-up steel reaction beam with a post-tensioning bar at each end. In this setup, force was applied monotonically through two 100 ton (890 kN) jacks, while a pressure transducer was used to monitor load. This setup is illustrated in Fig. 4.

EXPERIMENTAL RESULTS AND DISCUSSION

Test results are presented in Table 2 alongside specimen geometry. Analysis of results comprises two parts: 1) qualitative discussion of observed failure; and 2) quantitative discussion of observed peak loads.

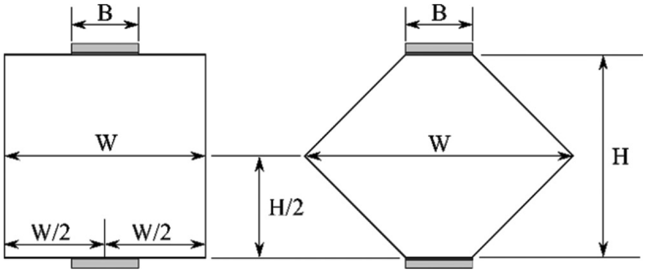

Fig. 3—Typical bottle specimen dimensions. (Note: B is out-of-plane dimension.)

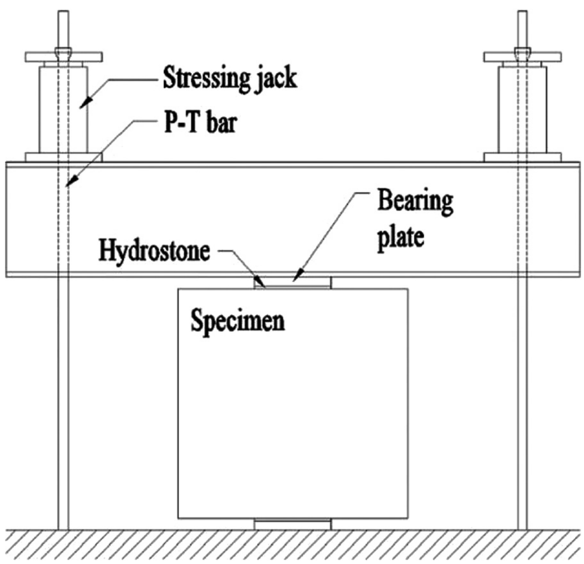

Fig. 4—Testing configuration for large specimens.

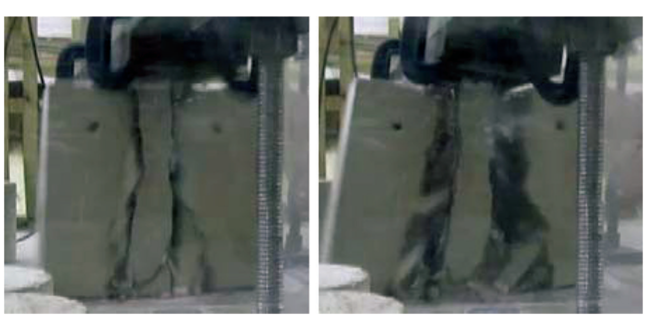

Fig. 5—Failure of Specimen C3-1 (from video footage).

Qualitative results

Typical failure in prismatic struts (W/B = 1) was sudden with well-defined compression wedges at the top and bottom loading surfaces. This is analogous to the failure observed in concrete cylinder compression tests, where cones are sometimes observed on the bearing surfaces as a result of friction.

In bottle struts (W/B > 1), longitudinal cracks were visible at stresses below the peak load. These struts typically failed by lateral bursting at approximately $0.9f_c'$ (Fig. 5). In many cases, a wedge similar to that observed for prismatic struts remained at the base plate after failure (Fig. 6).

Quantitative results: effect of shape (*W/B*)

The peak loads measured in this investigation were first expressed in terms of experimental strut efficiency factors

Fig. 6—Specimen C3-2 after failure.

Table 3—Statistical summary of strut efficiency factors for specimens tested in this study

Series	W/B	Strut efficiency factor $\beta_e = f_b/0.85f_c'$		
		Mean	Minimum	Coefficient of variation, %
(1)	(2)	(3)	(4)	(5)
Series A	1	1.29	1.19	5.7
	2	1.03	0.97	8.9
	3	1.12	0.98	10.9
	4	1.03	0.96	6.7
	All	1.15	0.96	12.3
Series B	1	1.03	0.94	4.5
	2	1.09	1.00	7.0
	3	1.05	1.02	3.5
	All	1.05	0.94	5.1
Series C	1	1.15	1.14	0.3
	3	1.02	1.00	1.0
	All	1.07	1.00	6.7
All Series	1	1.16	0.94	11.7
	>1	1.06	0.96	7.0
	All	1.10	0.94	10.5

using Eq. (1). For all specimens tested, f_c' in this equation was established at test day. Table 3 presents a statistical summary of the results from the three series of tests conducted in this study.

The test results from this study were combined with the test results from past studies in the database. Because the focus of this investigation is strength, the database was narrowed to include only tests in which peak load was reported. For this reduced set, mean experimental efficiency factors were selected as an initial basis for comparison, and are plotted against W/B in Fig. 7. Note that the mean experimental efficiency factors obtained from the tests of large 1-D and 2-D struts in this study are consistent with those of past

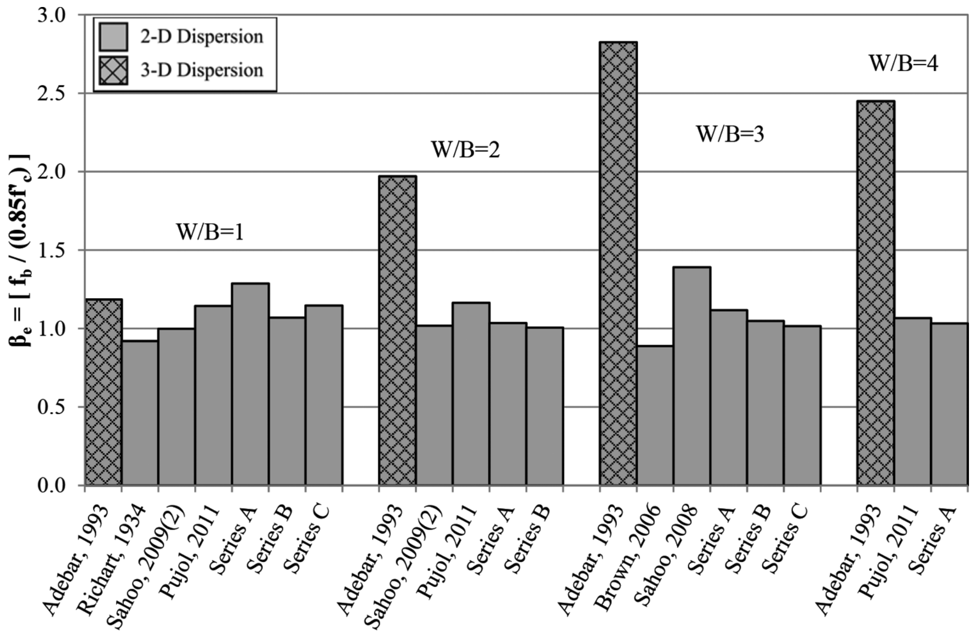

Fig. 7—Mean experimental efficiency factors across various studies for selected W/B.

investigations conducted using smaller specimens (Pujol et al. 2011; Sahoo et al. 2009b).

Bottle struts with 3-D stress dispersion are denoted by hatched bars in Fig. 7, while solid bars denote bottle struts with 2-D stress dispersion. On average, bottle struts with 3-D dispersion showed higher efficiency factors than 2-D struts. This can be attributed to confinement (Adebar and Zhou 1993). Such confinement is not possible in a 2-D bottle strut, which explains why 2-D bottle struts tested in this study saw little variation in efficiency factor across all *W*/*B*, with a mean of 1.06.

Because group efficiency factor was skewed by the inclusion of 3-D struts (which have confinement contributing to strength that is not present in 2-D struts), the data set was reduced to exclude these 3-D struts. For the reduced data set (containing 116 tests), experimental efficiency factor is plotted against *W*/*B* in Fig. 8. The most prominent features of this figure are the wide scatter across all *W*/*B* and the lack of a well-defined positive or negative trend. Figures 7 and 8 provide no clear evidence to support the idea that increasing *W*/*B* has a negative impact on strut strength (for 2-D struts).

Quantitative results: other factors

Improved curing conditions reduced the coefficient of variation of experimental strut efficiency factor for a given *W*/*B*. Despite this reduction in scatter, the mean efficiency factors for Series A, B, and C remained nearly the same (within 10% of each other). Aggregate size also had no clear impact on efficiency factor.

SUMMARY AND CONCLUSIONS

The majority of published literature about unreinforced concrete struts states that the unit compressive strength of a plain strut loaded in compression across its full cross-sectional width (prismatic strut) is greater than that of the same strut loaded over a reduced width (bottle strut). The reason provided for this reduction in unit strength is that the internal

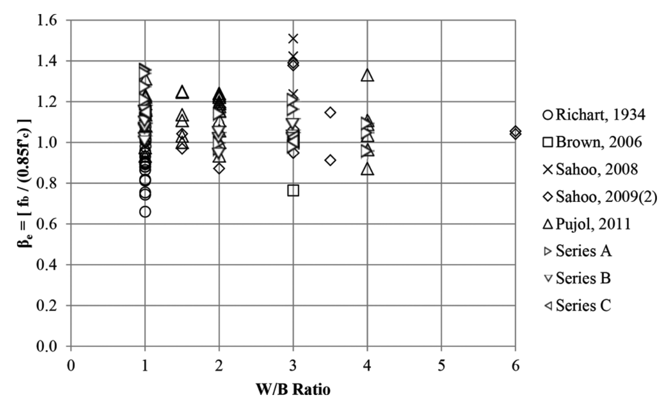

Fig. 8—Plot of experimental strut efficiency factor for 2-D dispersion and peak load.

spread of stresses in a bottle strut gives rise to internal tensile stresses, which cause splitting failure before the strut can develop its full compressive strength.

The hypothesis that planar bottle struts are weaker than prismatic struts was examined in this study. To fill a gap in existing data related to specimen size, 32 unreinforced specimens were tested in compression to failure. The tests results were combined with other results from tests conducted on similar specimens to produce a database of unreinforced struts, which was made accessible online. In contrast to current published engineering consensus, the data showed no clear and consistent trend to support the hypothesis that prismatic struts possess higher unit strength than planar bottle struts. On average, bottle struts attained compressive strengths comparable to the strengths of prismatic struts, regardless of their *W*/*B*. Presumably, as B decreases and *W*/*B* tends to infinity—as in the case of a load applied over a knife's edge—bearing stress should exceed f_c'.

AUTHOR BIOS

ACI member **Lucas Laughery** *is a Graduate Student in the Department of Civil Engineering at Purdue University, West Lafayette, IN. He received his*

BS in civil engineering and architectural engineering from Missouri S&T, Rolla, MO, in 2012 and his MSCE from Purdue University in 2013.

ACI Fellow **Santiago Pujol** *is an Associate Professor in the Department of Civil Engineering at Purdue University. He is a member of ACI Committees 133, Disaster Reconnaissance; 314, Simplified Design of Concrete Buildings; and ACI Subcommittee 318-R, High-Strength Reinforcement; and Joint ACI-ASCE Committee 445, Shear and Torsion. He received his BSCE from National University of Colombia, Bogota, Colombia, in 1996, and his MSCE and PhD from Purdue University in 1997 and 2002, respectively.*

ACKNOWLEDGMENTS

The authors would like to acknowledge Bowen Laboratory for Large Scale Structural Engineering for providing the necessary facilities and equipment to conduct these tests. They would also like to thank those students who were involved in the care and testing of specimens. They include R. A. Louzi, R. Jenkins, E. Villalobos, and Y. Wang.

NOTATION

B	=	bearing plate width
D	=	depth of specimen
f_b	=	bearing stress
f_c'	=	compressive strength of concrete cylinder
H	=	height of specimen
i	=	i-th reference listed
m	=	total number of references
n	=	number of specimens reported in reference i
W	=	width of specimen at midheight
β_e	=	experimental strut efficiency factor

REFERENCES

Adebar, P., and Zhou, Z., 1993, "Bearing Strength of Compressive Struts Confined by Plain Concrete," *ACI Structural Journal*, V. 90, No. 5, Sept.-Oct., pp. 534-541.

Brown, M.; Sankovich, C.; Bayrak, O.; and Jirsa, J., 2006, "Behavior and Efficiency of Bottle-Shaped Struts," *ACI Structural Journal*, V. 103, No. 3, May-June, pp. 348-355.

Pujol, S.; Rautenberg, J.; and Sozen, M., 2011, "Compressive Strength of Concrete in Nonprismatic Elements: Experimental Studies of the Bottle-Shaped Strut," *Concrete International*, V. 34, No. 9, Sept., pp. 42-49.

Richart, F., and Brown, R., 1934, "An Investigation of Reinforced Concrete Columns," *Bulletin 31*, No. 40, June, University of Illinois, Urbana, IL.

Sahoo, D. K.; Bhargava, P.; Singh, B.; and Gautam, R. K., 2008, "Strength and Deformation Characteristics of Bottle-Shaped Struts," *Magazine of Concrete Research*, V. 60, No. 2, Mar., pp. 137-144. doi: 10.1680/macr.2008.60.2.137

Sahoo, D. K.; Singh, B.; and Bhargava, P., 2009a, "Investigation of Dispersion of Compression in Bottle-Shaped Struts," *ACI Structural Journal*, V. 106, No. 2, Mar.-Apr., pp. 178-186.

Sahoo, D. K.; Singh, B.; and Bhargava, P., 2009b, "An Appraisal of the ACI Strut Efficiency Factors," *Magazine of Concrete Research*, V. 61, No. 6, Aug., pp. 445-456. doi: 10.1680/macr.2008.00112

NOTES: