Disc. 102-S83/From the Nov.-Dec. 2005 *ACI Structural Journal*, p. 823

Fiber-Reinforced Polymer Strengthening of Concrete Bridges that Remain Open to Traffic. Paper by Michael W. Reed, Robert W. Barnes, Anton K. Schindler, and Hwan-Woo Lee

Discussion by Richard A. Barnes

PhD, CEng, MICE, Lecturer, Engineering Systems Department, Cranfield University (Defence College of Management and Technology), Swindon, UK

The authors are to be congratulated on their contribution to knowledge regarding the FRP strengthening of concrete bridges that remain open to traffic. Other previous work that the authors have not reviewed, but that provides useful information, include References 9 and 10.

In summarizing all of the work (including that reviewed by the authors and indeed their own work) done in this area, it is important to recognize that traffic vibration during curing would appear to have an effect on the strength of the adhesives typically used for this application. However, as the failure plane in an FRP strengthened concrete beam is typically within the concrete, the weakening of the adhesive does not affect the overall load capacity of the strengthened beams.

This is an important point to make note of, as in a CFRP-strengthened member, such as a steel beam, where the failure would be within the adhesive layer, vibration from traffic loads *is* likely to lead to a reduction in ultimate capacity of the strengthened member.

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Disc. 102-S84/From the Nov.-Dec. 2005 *ACI Structural Journal*, p. 832

Repeating a Classic Set of Experiments on Size Effect in Shear of Members without Stirrups. Paper by Evan C. Bentz and Sean Buckley

Discussion by Zdenek P. Bažant and Mohammad T. Kazemi

FACI, Department of Civil Engineering, Northwestern University, Evanston, Ill.; Sharif University of Technology, Tehran, Iran

The authors' interest in the classical Northwestern University tests by Bažant and Kazemi in 1991,[10] is deeply appreciated. In view of the expertise of the authors' laboratory in the testing of concrete structures, the test results reported will surely represent a valuable addition to the literature. The authors' test results, however, are misinterpreted in a way that favors Bentz's previous arguments within ACI Committee 445 for excluding these classical tests from the ACI-445F database and supports his persistent opposition in that committee to the fracture mechanics concept of size effect, which contradicts the Toronto concept of size effect in shear.[24-26]

The only correct and unbiased conclusions from the authors' test results is that they: 1) support the validity of the aforementioned classical tests; 2) corroborate the fracture mechanics size effect revealed, among other evidence, by these classical tests; and 3) demonstrate that these classical tests should not have been excluded from the ACI-445F database.[23,27-28] Some of the causes of the authors' incorrect interpretation of their test results are as follows.

1. *Was it a "repeat" of the classical tests?*—It was not. The classical test specimens were reduced-scale models intended to achieve a high brittleness number[29] and thus inexpensively simulate the behavior of large normal concrete beams having such a brittleness number. The authors, however, tested medium-size normal concrete beams of a lower brittleness number, which were very different in many respects—a different concrete mixture, the maximum aggregate size more than doubled, the steel bars differently scaled and differently arranged, a different loading rate, a different loading process with undesirable loading stops, and a much reduced size range (1:2:4 instead of 1:2:4:8:16), with the two largest sizes omitted. It is a pity that the authors have not tested beams scaled-up eight and 16 times, that is, up to the depth of 1.6 m.

Reproducibility of test data is the basic requirement of science, but it means that the repeated tests must be identical (as nearly as possible). The fact that the authors, in their effort to disprove the classical reduced-scale tests, did not actually try to reproduce them is strange because the beams of the classical tests were much smaller and thus much easier and cheaper to test. If the authors believed that the aggregate size of 4.8 mm, used in the classical tests, was meaningless, they should have tried to prove it by testing both the small beams identical to the classical tests and the large beams with doubled aggregate size, and then make comparisons. Were the authors afraid that reproducing these classical tests would confirm their validity and thus disprove the Toronto concept of size effect in beam shear?

2. *No difference found in size-effect trends*—Plotting the size effect curves from the authors' and the classical tests in linear scales, the authors achieve, in Fig. 11, a false impression of a very different trend, and then they try to capitalize on it in their argument against the validity of the classical tests. According to the fracture mechanics-based size effect

formula, $v_c\sqrt{f_c'} = v_0\sqrt{1 + d/d_0}$, however, proposed for beam shear by Bažant and Kim in 1984,[30,31] a change in the type of beam properties should not produce similar size effect curves in the linear plot of shear strength v_c versus beam size (depth) d, used by the authors ($v_c = V_c/b_w d\sqrt{f_c'}$). Rather, it should produce similar, mutually shifted curves in the logarithmic scales, that is, in the diagram of $\log v_c$ versus $\log d$.

If the authors' data (from Fig. 11 and Table 1) are replotted in such a diagram, similar curves do result (refer to Fig. A(a)). If one finds the optimal values of v_0 and d_0 for each test series, then the authors' tests match the classical tests as closely as might be desired (within inevitable random scatter), and they both closely fit the same size effect curve in dimensionless coordinates (Fig. A(b)).

The correct conclusion, therefore, is that the authors' data are in excellent agreement with the classical tests of Bažant and Kazemi in 1991,[10] and thus support their validity. Hence, these classical tests must no longer be excluded from the database of ACI Committee 445.

This conclusion would become stronger if the authors did not restrict their test series to beams of three sizes only (scaled as 1:2:4) and tested beams of given sizes (scaled as 1:2:4:8:16) as used in the classical tests. Note also that if the omitted tests of two enlarged beams were actually carried out, they would be (according to the fracture mechanics-based theory of size effect) expected to yield approximately the asterisk points shown in Fig. A(a). This is a speculation to be checked.

3. *Asymptotic slope of logarithmic size effect curve reconfirmed*—The main consequence of fracture mechanics is that the asymptotic slope of the plot of $\log v_c$ versus $\log d$ should be –1/2. The authors' results for their largest and medium-size beams agree with this fundamental property very well—in fact, better than one would expect in view of unavoidable random scatter (Fig. A(b)).

4. *Closing comment*—The authors' test results are deeply appreciated. They lend additional support to the fracture mechanics theory of size effect in reinforced concrete.

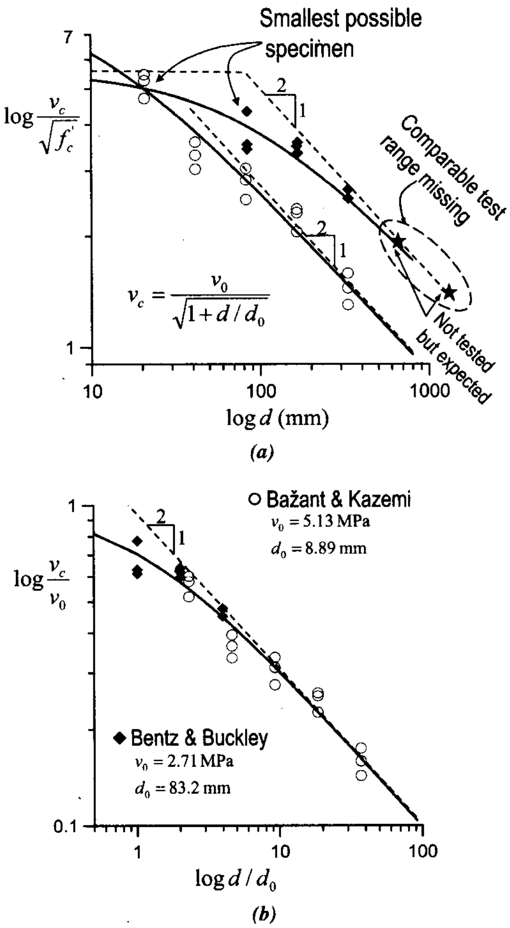

Fig. A—Classic Bažant and Kazemi[10] tests (empty circles) and authors' tests (diamonds) replotted in logarithmic scales: (a) nominal shear strength versus beam depth (size); and (b) the same, but in dimensionless coordinates.

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Disc. 102-S84/From the Nov.-Dec. 2005 *ACI Structural Journal*, p. 832

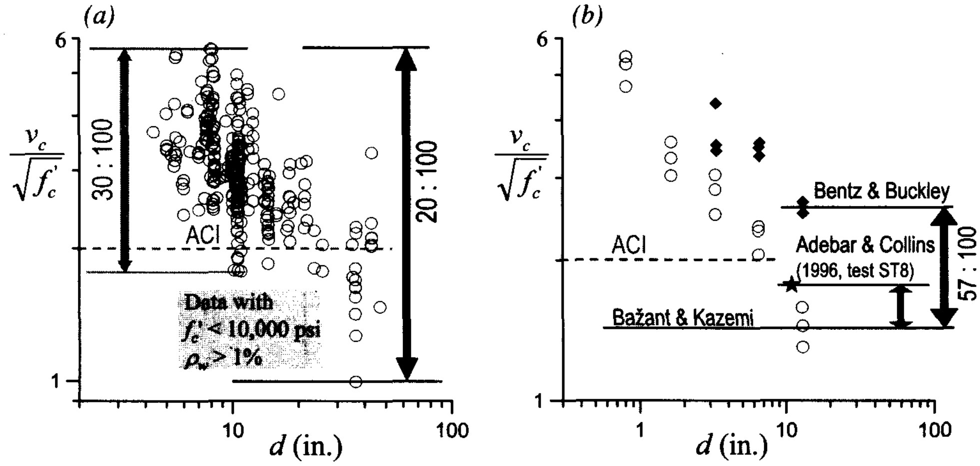
Repeating a Classic Set of Experiments on Size Effect in Shear of Members without Stirrups. Paper by Evan C. Bentz and Sean Buckley

Discussion by Qiang Yu and Zdenek P. Bažant

Hachinoche Institute of Technology, Hachinoche, Japan; FACI, Department of Civil Engineering, Northwestern University, Evanston, Ill.

The authors' test results represent a valuable expansion of the database for beam shear. The authors' interpretation, however, is not correct. Some of the reasons for rejecting the authors' interpretation are as follows:

1. *Proper interpretation in the light of known random scatter*—The authors base their critique of Bažant and Kazemi's classical tests[10] exclusively on the difference between the size effect curves of the classical and their own



		d (in.)	a/d	f_c' (psi)	ρ_w %	Agg. (in)	f_y (ksi)
◆	Bentz & Buckley	13.0	3.0	4931	1.62	0.39	58
○	Bažant & Kazemi	13.0	3.0	6700	1.62	0.19	100
★	Adebar & Collins	10.94	2.88	6699	1.95	0.39	77.7

Fig. B—(a) ACI-445F[23] database for beam shear (excluding classical tests). Note scatter range when type of concrete varied; and (b) difference between authors' tests and classical tests, to be compared with (a).

tests. This difference, however, which is best appraised in logarithmic scales, as shown in Fig. A(a) of the preceding discussion by Bažant and Kazemi (and not the linear scales used by the authors in their Fig. 11), must have been expected in view of the scatter evident in the ACI-445F database[23] (compiled from 398 beam shear tests) (refer to Fig. B(a)). This database covers diverse concretes, aggregate sizes, rates of loading, loading procedures, shear span ratios, and steel ratios. For the size range of the classical and the authors' tests, this diversity is seen to cause v_c to scatter within the ratio of about 30:100. For the classical and the authors' tests, the measured v_c values differ in the ratio of approximately 57:100. This is almost within the scatter range seen in the database when lightly reinforced beams are excluded and only normal concretes are considered. So, as can be seen, the differences between the classical and the authors' tests (Fig. B(b)) are not surprising at all. They agree very well with the scatter documented by the ACI-445F database.[23]

2. *Scatter in the effect of changing maximum aggregate size* d_a—Consider now specifically the scatter of v_c caused by changing d_a alone. Figure C (based on References 25 and 26) shows the ACI-445F database[23] when the effect of d_a alone is isolated (which is achieved by plotting, as the ordinate in Fig. C, a parameter of v_c from which the effects of shear span and steel ratio have been eliminated, in the mean sense [refer to Reference 26]). The regression line, having the optimum slope of 1/2 (Fig. C), would predict the authors' beams to be only 21% stronger, but actually they were 77% stronger. Because of the huge scatter of the test data in Fig. C, however, the optimum is weak, and the line of slope 2/1 happens to fit the data cloud in Fig. C almost equally well. That line would predict v_c from the classical and the authors' tests to be approximately in the aforementioned ratio of 57:100, if the aggregate size was the only difference.

Therefore, it must be concluded that the difference between the authors' and the classical tests is well within the known scatter range when the aggregate size and type are varied.

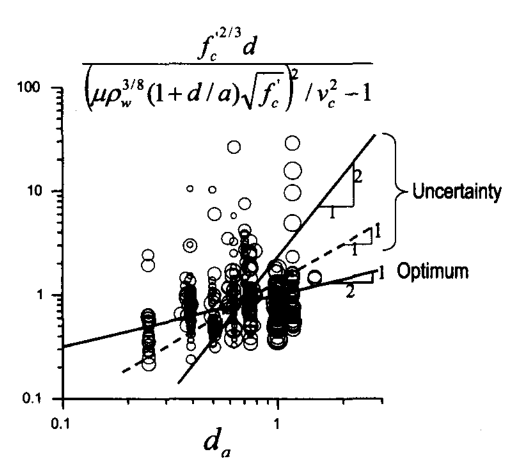


Fig. C—Scatter of nominal strength parameter when only maximum aggregate size d_a is varied, and various straight lines that can describe rising trend of data cloud almost equally well.

3. *Differences due to loading stops and loading rate changes*—During the interval from 5 minutes to 2 hours after sudden load application, creep causes the deformations of concrete to increase by approximately 20% in the service stress range, and much more on approach to the peak stress. Therefore, attention must be paid to the loading rates. To be comparable, tests of different sizes should be loaded monotonically and at constant rates such that the test duration up to the peak load be reached at approximately the same time (this assures the fracture process zones in specimens of different sizes to be loaded at approximately the same rate).

For the classical tests, the loading was monotonic, with constant stroke rates, adjusted so that the peak load would be reached within approximately 7 minutes for all the sizes. For the authors' tests, the duration of all tests (from the start of loading to the peak load) is reported to be approximately 2 hours. This means that, in the authors' tests, the creep deformations were much more pronounced than in the classical tests.

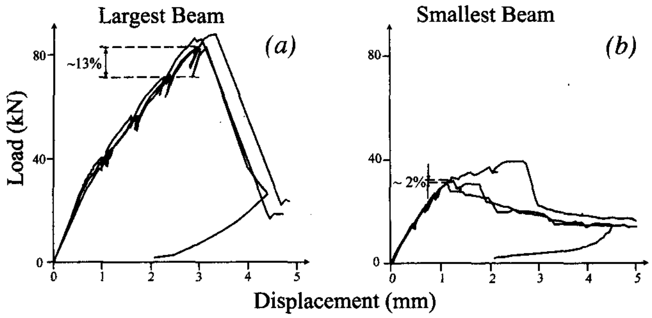


Fig. D—Relaxation of applied shear force due to creep during load stops and its different magnitudes when: (a) largest; and (b) smallest beams of authors are compared.

The authors' load-deflection diagrams for the largest and smallest beams are plotted in Fig. D, where it should be noted that, during the load stops, the load relaxed (due to creep) by approximately 13% in the largest beams but only by approximately 2% in the smallest beams. This must have disturbed similarity and comparability of the tests of the largest and smallest beams.

The loading stops used by the authors to allow tracing the cracks on the beam surface with a pen are undesirable, not only because they cause creep but also because they introduce partial unloading (a partial reversal and decrease of the load-point deflection, because of elastic rebound of the test frame as the load relaxes due to creep). Because, for small beams, there are fewer cracks to see by the eye, the load stops are fewer and shorter for small beams than for large beams, as can be noticed in the authors' Fig. 4 and 5 of their load-deflection records. This again compromises comparability.

The ancient technique of stopping the loading to allow visual tracing of the cracks should be replaced by automatic electronic high-resolution optical scanning of the cracked beam surface. This will allow monotonic loading at a constant prescribed rate and thus eliminate errors due to loading stops, which perturb mutual comparability of tests.

4. *Conflict of authors' results with another test in their own laboratory*—Figure B(b) also shows, by an asterisk, the result of one previous test in the authors' laboratory reported by their colleagues Adebar and Collins[16] (Test No. ST8). The geometrical shape, loading, concrete type, and steel ratio in that previous test happened to be almost exactly the same as for the largest beams of the classical tests (refer to Fig. B(b) with the table underneath). What should now be noted is that this test result is extremely close to the classical test results and differs enormously from the authors' result (see the asterisk in Fig. B(b)). Didn't the authors know this test result from their own laboratory, conflicting with their own conclusions and supporting the classical tests? It is strange that they have not mentioned this discrepancy.

5. *Conclusion*—The correct conclusion is that the authors' test results validate Bažant and Kazemi's[10] classical tests, demonstrate that these tests should not have been excluded from the ACI-445F database, and reinforce the fracture mechanics theory of size effect in beam shear. This conclusion also documents that reduced-scale testing on micro-concrete, if properly interpreted, is a valuable tool, which has been undeservedly shunned by many concrete researchers.

Disc. 102-S84/From the Nov.-Dec. 2005 *ACI Structural Journal*, p. 832

Repeating a Classic Set of Experiments on Size Effect in Shear of Members without Stirrups. Paper by Evan C. Bentz and Sean Buckley

Discussion by Mohammad T. Kazemi and Vahid Broujerdian
Sharif University of Technology, Tehran, Iran; PhD student, Civil Engineering Department, Sharif University of Technology

The authors are complimented for their repeat experiments. The tests, however, are much different from the original series[10] than what they claimed. Also, the test series of the authors do not adhere to geometrical similarity as closely as the original tests. The reported load-deformation responses exhibit a softening post-peak behavior that gets steeper for larger beams. The softening behavior, and the authors' observation that all the beams failed with little warning, coupled with the fact that similar stable shear cracks have developed before the peak load, support Bažant and Kazemi's[10] conclusion that shear failure of reinforced concrete beams and the resulting size effect need to be explained on the basis of fracture mechanics. From their Fig. 11, the authors concluded that linear elastic fracture mechanics is not a reliable basis for the size effect on strength. This is why Bažant and Kazemi[10] modeled the size effect according to nonlinear (or cohesive, quasibrittle) fracture mechanics.

The average values of failure loads based on nominal flexural strength of the beams are approximately 34, 68, and 102 kN for the smallest, medium, and largest beams, respectively. Comparing these estimated failure loads for the flexural failure mechanism, which produces no significant size effect, with the failure loads reported by the authors, indicates that their smallest beams did not reach their full shear capacity. Indeed, the smallest beams failed in a mixed shear-flexural failure mode that involved concrete crushing. In the original tests, the reinforcement had a minimum yield strength of 690 MPa instead of 400 MPa of the new tests. Had the authors used similar steel reinforcement, that is, higher yield strength or a higher steel ratio, their smallest beams would have failed purely by shear and would have given a higher shear strength compared to the medium and largest beams. This would make the match with Bažant's size effect law as close as in Bažant and Kazemi's tests.

To overcome the difference in strength, the authors' normalized beam strengths v_c by $\sqrt{f_c'}$. The size of beams, however, should be normalized, too, by introducing a size scale. Various size scales have been proposed. Recently, Kazemi and Broujerdian[32] introduced a new relation for depth scale

$$d_s = \frac{\rho E_s(d_a + 16)}{100(a/d)\sqrt{f_c'}} \quad (1)$$