

Table A13.2-1, as stated in Section CA13.2 of the AASHTO LRFD specifications.¹⁶

3. The design forces of Table A13.2-1¹⁶ may not be derived by assuming a normal impact, and the crash angles of approximately 15 to 25 degrees presented in Table 13.7.2-1¹⁶ are accounted for. A similar procedure can be found in a formula proposed by Olson et al. and presented in NCHRP Report 86,²⁷ which is used to convert the vehicle crash effect into the equivalent transverse force applied to a railing. It can be seen that the crash angle is included in the formula.

The transverse forces of Table A13.2-1 were considered in the test because they are the dominant factors affecting the yield line pattern and ultimate strength of the barrier, as explicitly demonstrated in Section A13.3.1 of the AASHTO LRFD specifications.¹⁶ It should be noted that the longitudinal forces of Table A13.2-1 are not directly related to the crash angles and are derived from the transverse forces and the friction coefficient between the barrier and a vehicle. It can be seen that the friction coefficient is assumed to be 0.333 in Table A13.2-1. In this respect, it should be noted that the oblique angles do not directly affect the yield line pattern of a barrier.

4. The authors do not insist that the static test of the barrier can represent all the aspects and structural behavior anticipated in the real crash of a vehicle. The purpose and usefulness of the static test compared to a final verification through the vehicle crash test were addressed in the introduction of the paper. The ratio of the two stiffnesses of a vehicle before and after the impact and the contact time during the impact are related to the vehicle crash test and computer simulation.

5. As shown in Fig. 2, the loop splice and mortar filling were the main tools of this study to ensure a robust joint between the precast concrete barriers and deck. As was addressed in the paper, the joint maintained a reasonable integrity up to the ultimate loads presented in Table 2. Without these types

of anchorage systems, the precast barriers would turn over or move outward when subjected to a vehicle crash and not attain a required ultimate load.

6. As has been repeatedly mentioned in response to the previous comments, the test of this study follows the procedure presented in Table A13.2-1 of the AASHTO LRFD specifications.¹⁶ Although the dynamic magnification factor is outside of the scope of this study, it should be noted that the impact velocity of a vehicle is taken into account in deriving the transverse design forces of Table A13.2-1, as is the case in the aforementioned formula of NCHRP Report 86.²⁷ This implies that at least some of the dynamic aspects of a vehicle crash are accounted for in establishing the equivalent design forces corresponding to the test levels. The authors believe, therefore, that reducing the magnitudes of the ultimate loads of Table 2 in consideration of the dynamic magnification factor is inconsistent with the usual procedure to determine the test level of the barrier according to Table A13.2-1.

7. A number of yield line patterns have been proposed for a variety of structural shapes, boundary conditions, loading patterns, and so on. The yield line pattern of this study has been proposed for the barriers that are longitudinally continuous and have a tapered section with some points of slope discontinuity (as used worldwide), whereas most of the yield lines that can be found in the previous studies or textbooks deal with a structure with a constant thickness. The authors believe that the experimental and analytical attempts to improve the conventional yield line shape presented in the AASHTO LRFD specifications¹⁶ should be considered, rather than the shape of the yield line itself.

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Distribution of Stirrups across Web of Deep Beams

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Discussion by Rafael Alves de Souza, João da Costa Pantoja, and Luiz Eloy Vaz

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The authors have presented the results of deep beams subjected to shear to evaluate the benefit of distributing stirrups across the web. By testing three full-scale deep beams using a very interesting procedure and adopting the number of stirrup legs distributed across the web and the amount of web reinforcement as the primary experimental variables, the authors were able to obtain a total of six tests. Based on these tests, the authors have concluded that the addition of closely spaced stirrups did not significantly improve the shear capacity or serviceability performance of deep beams with a shear span-depth ratio (a/d) of 1.84 or 1.85. Despite the quality of their research, some additional issues should be discussed to clarify some topics and enhance the entire comprehension of this interesting paper.

INTRODUCTION

The authors state that the assumptions of a linear-elastic analysis usually assumed for designing beams are not valid

for deep beams; therefore, another analytical method, such as the strut-and-tie model (STM), must be employed. In fact, there are other available methods that could be used for this task, such as stress fields,¹³ the stringer panel model,¹⁴ and finite element procedures optimized for membrane action design¹⁵ and analysis.¹⁶ Strut-and-tie modeling can undoubtedly provide fast solutions for engineers when compared to the other alternatives.

Unfortunately, the authors do not provide clear information regarding the deep beam behavior and, perhaps for this reason, some difficulties arise when interpreting their results based on the STM approach.

A deep beam is a beam with a large depth-thickness ratio and a short a/d ($a/d < 2.0$); therefore, its behavior is completely different from that expected for slender or inter-mediated beams. Deep beams present two-dimensional behavior, whereas ordinary beams present one-dimensional behavior (B-region, beam, or Bernoulli region). Also, the

assumption of plane sections is not valid, as the shear deformation cannot be neglected (D-region or disturbed region) in deep beams.

As stated by the authors, the mechanism of shear transfer predominantly results from compressive stresses flowing directly from the load to the support; therefore, the capacity of a simple deep beam is dependent on the compressive strength of the concrete in the strut. As the shear transference is mainly made by a concrete strut and a tension tie, the authors are right in their conclusions regarding vertical stirrups across the web of deep beams—that is, for deep beams, the transverse reinforcement is only necessary for cracking control and for improving deformation capacity. In the discussers' opinion, horizontal stirrups distributed across the web could work better than vertical stirrups, as these can be more effective for controlling tensile strains in the bottle struts. What do the authors think about this opinion, taking into account their experimental experience?

The discussion about one- or two-panel behavior for shear transference is good, but it should include more significant details. The authors did not explain, for example, the “arch effect” that frequently occurs to better explain the shear transference in deep or slender beams with concentrated loads near the supports. Because of the “arch effect,” the tensile force in the longitudinal reinforcement of deep beams is constantly maintained, as seen in pile caps, dapped beams, and corbels. This behavior is completely different for a slender beam, where the tensile force in the longitudinal reinforcement presents variations along the beam, whereas the internal level arm is kept constant. This information would be useful, for example, to better explain the experimental results section and the conclusion that the distribution of vertical reinforcement across the web of a deep beam has a minor influence on the shear capacity.

The authors state that when the a/d exceeds a value of 2, the mechanism of shear failure is better characterized by a sectional shear (beam model), as the shear resistance of the beam is dependent on the cross section and the tensile resistance of the vertical stirrups. The authors are right, but in fact it is just a simple suggestion of limit value based on the Saint-Venant's principle, as it is difficult to propose a generalization of transition (deep beam behavior to slender beam behavior). Despite this problem, could the authors indicate for the assumed transition situation ($a/d = 2$) which model would demand more longitudinal reinforcement? In the discussers' opinion, for that situation, the effective depth may overestimate the shear strength and could demand more flexural reinforcement while using a beam approach.

RESEARCH SIGNIFICANCE

As mentioned by the authors, there is not a consensus as to whether the spacing of stirrups should be limited across the web of a deep-beam region. They also mentioned that past research has examined this matter for beams with an a/d greater than 2, but similar studies have not been conducted for deep beams. In the discussers' opinion, there is no research on this topic because the vertical stirrups have only had a minor importance in the shear strength of deep beams¹⁷ since the 1960s. Also, ensuring equilibrium and assuming that the longitudinal reinforcement will experience yielding before the crushing of the diagonal concrete struts is a simple condition for obtaining a collapse load higher than the design load, as provided by the lower-bound theorem of the theory of plasticity.^{18–20} Therefore, in the discussers' opinion,

the web reinforcement applied to D-regions is needed just to better control the cracking propagation or enhance critical bottle struts with additional horizontal stirrups.

EXPERIMENTAL PROGRAM AND EXPERIMENTAL RESULTS

The test setup section explains that the beams were monotonically loaded in approximately 50 kips (220 kN) and that for each load increment, the maximum width of any diagonal crack was recorded on both sides of the shear span under investigation. In the discussers' opinion, it is a very large step in a way that would be difficult to understand the crack width evolution without an abrupt variation. Could the authors explain how they determined this large load step?

Regarding the strength results section, the authors state that the failure of each test region was typically preceded by the crushing of concrete in the nodal region adjacent to the load plate and, therefore, it was more appropriate to normalize the shear capacity by the compressive strength of the concrete than the square root of the compressive strength. Could the authors better explain this last assertion and how to analyze the meaning of the last columns in Table 3?

SUMMARY AND CONCLUSIONS

The authors have presented a very interesting paper concerning the behavior of deep beams and they should be complimented on their research. Based on the test results, the authors were able to demonstrate that web reinforcement and the number of stirrups slightly influence the shear strength of deep beams with an a/d of less than 2. In fact, the obtained results could already be expected, taking into account the use of an STM. Taking into account the lack of experimental results for the deep beams with an a/d of less than 2, however, the authors had an opportunity to extend the data bank that is available for deep beams. The authors are encouraged to research the application of steel fibers and passive spiral confinement reinforcement for the diagonal struts, as the authors are concerned about the enhancement of the shear strength of deep beams.

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AUTHORS' CLOSURE

The authors thank the discussers for their comments and offer a few comments to close the discussion.

1. The discussers are reminded that, within limited space available for a technical paper, as the authors, we stated the objectives for the paper, presented experimental facts that guided our thinking, and reached conclusions that were based on experimental evidence and consistent with the objectives. As such, the authors will only comment on the facts presented in the subject paper. The authors will not speculate on some experimental variables that have not been studied.

2. The discussers suggest that horizontal stirrups may be more effective than vertical stirrups at controlling tensile strains in bottle-shaped struts. This topic was purposely not discussed in the subject paper because it is relatively complex and deserves more attention than permitted by the length requirements. With that said, the discussers are referred to the commentary of ACI 318-08,⁵ Sections R11.7.4 and R11.7.5, which state that "tests have shown that vertical shear reinforcement is more effective than horizontal shear reinforcement." The authors conducted a database analysis of previous deep beam shear tests and were able to further substantiate the aforementioned commentary.⁴ The authors refer the discussers to the authors' research report⁴ for further information regarding the effectiveness of reinforcement in deep beams.

3. The specimens presented in this paper were specifically configured to evaluate the effectiveness of distributing transverse reinforcement across a beam's web. Again, the authors refer the discussers to the authors' research report⁴ for information with respect to the effectiveness of the reinforcement

ratio and the transition region between deep and slender beam behavior. These topics are complex and nuanced and deserve much more attention than could be discussed within the limitations of the subject paper.

4. As spelled out in the paper, the authors are in agreement with the discussers regarding the effectiveness of shear reinforcement in deep beams with respect to strength. The effectiveness of distributing shear reinforcement across the web of a deep beam, however, is an important topic in view of the fact that AASHTO LRFD specifications⁷ (Fig. 4) require a minimum amount of distribution, and there is a sparse amount of guidance provided elsewhere. The implications of stirrup detailing on serviceability are a different issue that was discussed in the paper.

5. The authors selected a load step equal to 10% of the expected final load, thereby resulting in at least 10 load increments until failure. Given the variability inherent in crack measurements, the load increments were deemed sufficient for determining the overall trends in crack width propagation.

6. Experimental loads that are associated with the tensile strength of concrete, such as the diagonal cracking load or the sectional shear (that is, diagonal tension) strength of a member, are typically normalized by $\sqrt{f'_c}$. Experimental loads that are associated with the compressive strength of concrete, such as the ultimate capacity of a deep beam, are typically normalized by f'_c . The authors based the findings of this study on the experimental results normalized by f'_c . Recognizing that many practitioners are familiar with shear values normalized by $\sqrt{f'_c}$, however, both types of values were presented with the results.

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