Discussion: Dynamic properties of large aggregate concrete under triaxial loading

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Based on an experimental investigation, Shi *et al.* (2015) analysed the dynamic properties of large aggregate concrete under triaxial tension–compression–compression loading states. Strain rates ranging from 10^{-5} to 10^{-2} s^{-1} and seven stress ratios were combined to obtain stress–strain relationships, tensile strength (σ_{1f}), critical strain (ϵ_{1f}), secant modulus (E_{sec1}) and failure modes. The authors should be complimented for producing this detailed paper of interest for the discussor, who would like to offer the following comments for the authors' consideration and response.

The authors state that σ_{1f} increases almost linearly with the logarithmic increase of strain rate. This can be observed in Figure 5. However, it seems that there are some inconsistencies regarding the depicted values and the average values included in Table 2. By way of example, according to Table 2, σ_{1f} is 1.25 MPa for 10^{-4} s^{-1} and 0.3:–1:–1, whereas a value about 1.20 MPa is depicted in Figure 5. In general terms, the values of σ_{1f} in Figure 5 are lower than the corresponding values in Table 2.

The discussor agrees with the authors' conclusion that σ_{1f} decreases as the absolute value of confined compressive stress increases. However, in the discussor's opinion, Figure 6(a) does not reflect the different compressive stress levels as all curves correspond to stress ratios with $\sigma_2 = \sigma_3 = -1$. Instead, the four stress ratios having $\sigma_1 = 0.1$ could offer a better option as σ_2 ranges from –0.25 to –1, which refer to different confined compressive stress levels. As observed in Table 2 for each strain rate, σ_{1f} decreases when $|\sigma_2|$ increases, more markedly between $\sigma_2 = -0.25$ and $\sigma_2 = -0.5$.

Regarding Figure 6(b), the authors detail that σ_{3f} reduced as the absolute value of σ_{2f} increased. However, the discussor notes that the four curves shown in Figure 6(b) correspond to the four stress ratios with $\sigma_1 = 0.1$. For the same stress ratio, σ_{3f} increases when σ_{2f} increases, and there is not any reduction in σ_{3f} based

on σ_{2f} : the specimens ruptured by one apparent tensile crack perpendicular to the direction of the applied tensile loading, and the curves directly reflect the fixed σ_3/σ_2 ratios.

The authors conclude that ϵ_{1f} increases with an increase in confined compressive stress at the same strain rate. This is observed in Table 3. However, the discussor points out that there are some exceptions concerning the 0.1:–1:–1 stress ratio with respect to the 0.1:–0.75:–1 stress ratio for strain rates of 10^{-4} , 10^{-3} and 10^{-2} s^{-1} .

Finally, the discussor notes that perhaps there are some errata and/or inconsistencies that may hinder understanding of the paper, as follows.

- 'Strain ratio' should be replaced with 'stress ratio' in Tables 2, 3 and 4.
- A 0.2:–1:–1 stress ratio should be detailed instead of –1:–1.0.2 in Figure 4.
- Figure 7 shows stresses σ_{su} and σ_{ru} instead of σ_3 and σ_1 , respectively.
- The expression for tangential octahedral stress presents the same term twice.
- It seems that some of the values included in Table 5 should be corrected (e.g. values of σ_{1f} for 0.1:–0.25:–1 are equal to 1.32, 1.45 and 1.68, not to 1.23, 1.40 and 1.63, respectively).

Authors' reply

After checking Figure 5, it was found that these inconsistencies are caused by a printing error of the grid lines of the y -axis (σ_{1f} -axis). The correct figure is given here as Figure 12.

With regard to the discussor's second point, there are two types of stress ratio that reflect the effect of compressive stress state on dynamic tensile strength. One type for the stress ratio $\sigma_1:\sigma_2:\sigma_3$ is 0.1:– x :–1, which means that σ_2 ranges from –0.25 to –1 when $-\sigma_1/\sigma_3 = 0.1$. Another type for the stress ratio

Figure 12. Influence of strain rate on σ_{1f}

Figure 13. Effect of intermediate stress ratio σ_2/σ_3 on tensile strength σ_{1f}

$\sigma_1:\sigma_2:\sigma_3$ is $x:-1:-1$, which means that σ_1 ranges from 0.05 to 0.3 when $\sigma_2/\sigma_3 = 1$. The purpose of the original work was to find the influencing effect of the intermediate stress σ_2 on σ_{1f} and σ_{3f} . Obviously, σ_{1f} reduces more apparently as the absolute values of both σ_2 and σ_3 increase than by only increasing the absolute value of σ_2 . The intermediate stress ratio should be expressed as σ_2/σ_3 , but in the published paper (page 288, line 1 of the left-hand column), it was written as $-\sigma_1/\sigma_3$, ($\sigma_2 = \sigma_3$), which is wrong in this form. As suggested by the discussor, the tensile strength σ_{1f} is plotted against the intermediate stress ratio σ_2/σ_3 for the case of 0.1 in Figure 13.

As mentioned by the discussor, the curves in Figure 6(b) in the published paper directly reflect the fixed σ_2/σ_3 ratios. Actually, it is better to plot the curve between $-\sigma_3$ and σ_2/σ_3 in order to show the effect of intermediate stress σ_2 on the maximum compressive stress at failure, although the specimen was fractured by tensile cracking. It is important to study the compressive strength of concrete under the stress states of tension and compression in the construction of concrete dams. However, for the case of $\sigma_1/\sigma_3 = 0.1$, $-\sigma_3$ is always 10 times σ_1 , so the tendency between $-\sigma_3$ and σ_2/σ_3 is similar to that of $\sigma_{1f}-\sigma_2/\sigma_3$. In a similar way, in order to investigate the failure surface of concrete, the relationship of σ_{2f} and σ_{3f} with fixed $-\sigma_1/\sigma_3$ can also be shown as 0 (biaxial compression stress state), 0.2, 0.3 and so on.

The conclusions of the paper were summarised from experimental results obtained over a wide range of stress states. The authors considered the confined effect or increase of ε_{1f} by increasing σ_3 , which was shown in Figure 10 of the original paper. As mentioned by the discussor, with an increase in intermediate stress σ_2 , ε_{1f} does not increase linearly, especially when the stress ratio σ_2/σ_3 is increased from 0.1:-0.75:-1 to 0.1:-1:-1; there is a reduction in ε_{1f} . It is worth noting that both increases and decreases in strain have been observed for concrete specimens under dynamic loading by different authors (Bischoff and Perry, 1991). In fact, for inherent heterogeneity and the large scatter of strain in concrete, more tests should be carried out.

Table 7. Increasing percentage of tensile strength and deformation with strain rate

Stress, strain, elastic modulus	Strain rate: s^{-1}	Strain ratio							
		1:0:0 (uniaxial T)	0.1:-0.25:-1	0.1:-0.5:-1	0.1:-0.75:-1	0.1:-1:-1	0.05:-1:-1	0.2:-1:-1	0.3:-1:-1
σ_{1f}	10^{-5}	1	1	1	1	1	1	1	1
	10^{-4}	1.18	1.32	1.23	1.19	1.19	1.20	1.18	1.33
	10^{-3}	1.39	1.45	1.40	1.30	1.30	1.28	1.39	1.47
	10^{-2}	1.59	1.68	1.63	1.58	1.64	1.54	1.57	1.64
ε_{1f}	10^{-5}	1	1	1	1	1	1	1	1
	10^{-4}	1.10	1.01	1.05	1.05	1.03	1.02	1.02	1.01
	10^{-3}	1.15	1.08	1.08	1.08	1.04	1.03	1.05	1.02
	10^{-2}	1.17	1.08	1.09	1.13	1.04	1.03	1.06	1.06
E_1	10^{-5}	1	1	1	1	1	1	1	1
	10^{-4}	1.08	1.33	1.12	1.13	1.20	1.19	1.11	1.32
	10^{-3}	1.15	1.33	1.29	1.18	1.26	1.26	1.33	1.40
	10^{-2}	1.30	1.54	1.43	1.36	1.49	1.48	1.48	1.50

The errors pointed out by the discussor exist. The authors appreciate the discussor's attentive work and respond as follows.

- In Tables 2, 3 and 4, 'stress ratio' should replace 'strain ratio'.
- In Figure 4, $-1:-1:0.2$ should be written as $0.2:-1:-1$.
- In Figure 7, stresses σ_{su} and σ_{ru} should be replaced by σ_3 and σ_1 , respectively.
- The expression pointed out by the discussor is the equation on page 289, line 5 of the right-hand column: the second term $(\sigma_1-\sigma_2)$ should be replaced by $(\sigma_1-\sigma_3)$.

- The values in Table 5 were checked and calculated again. Table 7 shows the corrected values in bold font.

REFERENCES

- Bischoff PH and Perry SH (1991) Compressive behavior of concrete at high strain rates. *Materials and Structures* **24**(6): 425–450.
- Shi L, Wang L, Song Y and Shen L (2015) Dynamic properties of large aggregate concrete under triaxial loading. *Magazine of Concrete Research* **67**(6): 282–293, <http://dx.doi.org/10.1680/macr.14.00225>.