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Re-evaluation of seismic capacity of interior beam-column joints

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Abstract

In spite of the fact that a wide variety of tests on joints of both interior and exterior types have been carried out since the 1960 s, there is no unique design philosophy common to different codes in the world. This is possibly due to the different interpretations of tests as well as test specimens with different demands. This study gives the preliminary findings of the investigations on the factors that effect the performance of interior joints under seismic loads. The authors inspected an experimental database by bringing different tests from different countries together. The database consisted of interior joints which are under uniaxial and biaxial seismic loading and specimens subject to vertical and horizontal acceleration. The experimental database includes tests from different countries such as New Zealand, Japan, the United States as well as the United Kingdom. The results of the parametric studies showed that concrete cylinder strength increased the joint shear strength, while the column axial load had no influence on the joint shear strength of cyclically loaded interior beam column connections. The authors also investigated the influence of joint aspect ratio. The results showed that as the joint aspect ratio is increased, the joint shear strength decreases. The authors examined the tests with respect to the countries. As a successful design is characterized by a failure mode in the beam, the authors are in the opinion that the most successful results were achieved by Japanese and New Zealand tests, as most of them failed in the beam. The authors inspection of the influence of stirrups on the joint shear strength showed that neither the stirrups nor the stirrup index influenced the joint shear strength but loading history was more influential in increasing the shear resistance of joints.

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1 Introduction

The design of cyclically loaded joints has always been a matter of debate between various codes in the world. Different codes adapt different design philosophies for the design of joints. Some codes rely on the so called strut mechanism; some on the truss mechanism. The strut mechanism stands for the concrete contribution to joint shear strength and represents the shear transfer across the joint by a direct compressive strut provided sufficient horizontal and vertical forces are available at the appropriate corners of the joint. A second mechanism by which shear may be counteracted is the truss mechanism which accounts for the stirrups in the joint. This mechanism consists of a truss which is formed by joint horizontal reinforcement and diagonal concrete struts. The above mentioned disagreements on the design of cyclically loaded joints necessitate the evaluation of the parameters effecting the performance of joints as a whole. The possible interaction of different parameters should also be considered. In the following sections, the influence of different parameters on the joint shear strength such as column axial load, concrete cylinder strength, joint aspect ratio (hb/hc), the ratio of the height of the column to the diameter of the beam bar, the ratio of stirrups, the yield stress of the transverse reinforcement will be investigated.

2 Parametric studies on the influence of different parameters effecting the normalized joint shear strength

2.1 Concrete cylinder strength

As the concrete strut is anticipated to transfer load at stresses substantially smaller than the crushing strength of joint concrete, it may seem that the amount of joint shear strength which can be assigned to this mechanism is independent of the crushing strength of the concrete. Nevertheless, the cracked concrete strength is a function of the concrete crushing strength [1,2] and in reality, as the concrete crushing strength increases, the joint shear strength increases. This means that the viability of the concrete strut mechanism relies on the availability of appropriate end conditions as well as the material strength of the strut. Furthermore, the concrete strength improves the bond strength of the flexural bars that provides the input shear to the joint. The authors made a parametric study on an experimental database consisting of tests of cyclically loaded interior joints subjected to uniaxial loading, such as Beckingsale [3], Birss [4], Durrani and Wight [5], Fuji and Morita [6], Joh, Goto, Shibata [7], Kitayama, Otani and Aoyama [8], Sugano [9], Ishibashi [10], Leon [11] and biaxial loading such as Leon [12] and vertical acceleration such as Higazy [13]. The results are shown in Figure 1. It is striking to see that the shear strength of the specimens with concrete cylinder strengths higher than 55 Mpa, are not as high as to be expected. One common aspect of these specimens is that all of these specimens belong to the group of experiments of Sugano. The authors compared the specimens of

Ishibashi which had medium concrete strengths and significantly high joint shear strengths with Sugano specimens. The loading histories of Ishibashi specimens showed that the specimens reached their maximum joint shear strength after 1, 2, 3, 4 ,5 or even 7 cycles. The Sugano specimens on the other hand reached their maximum joint shear strengths after 2 to 4 cycles. Loading histories do not seem to explain the difference in joint shear strengths. The Sugano specimens had a joint aspect ratio of 0.91, while the Ishibashi specimens had a joint aspect ratio of 0.91 to 1.2. The Ishibashi specimens were full scale compared to the Sugano specimens which had smaller beam and column cross sections as well as low values for beam length and column height. Smaller specimens have higher joint shear strengths with respect to greater size specimens. As we will explain later, the joint aspect ratio decreases the joint shear strength rather than increase it. The above arguments do not explain why the specimens of Ishibashi had higher joint shear strengths compared to Sugano specimens. Some of the low joint shear strength could be attributed to the normalization process; however the authors are in the opinion that the possible low strength of these specimens are due to these specimens failure modes. None of the Sugano specimens failed by anchorage failure. All of them failed by beam or a combination of beam and joint shear failure. The above argument shows that failure modes are very influential on the joint shear strength. If bond failure occurs in the joint, the truss mechanism disappears and the strut mechanism is enhanced. This increases the joint shear strength of specimens that fail by anchorage failure with respect to the ones that fail by other failure modes. Nearly all of the Ishibashi specimens which had high joint shear strengths (except series 4) failed by anchorage failure, except one specimen -D41No:1- which had a low hc/db ratio (=12) and relatively high concrete cylinder strength, which explains why it still had a high joint shear strength. Overall, Figure 1 does not give much clue on the influence of concrete cylinder strength to the joint shear strength. Other factors seem to be more dominant on joint shear strength rather than concrete cylinder strength. Nevertheless, the inspection of one series of tests indicates that concrete cylinder strength increases the joint shear strength.

2.2 Column axial load

Figure 2 shows the relation between the column axial stress normalized by the concrete cylinder strength and the normalized joint shear strength. It had been previously suggested by some researchers that the column axial stress increases the joint shear strength. However, the authors parametric study in Figure 2, clearly shows that this is not true. The column axial load has certainly no influence on the joint shear strength.

In the second series of tests in which the specimens were subjected to biaxial loading, the specimens BCJ8 and BCJ9 did not have axial load while the rest of the specimens were loaded with axial loads of 300 kN. The comparison of BCJ5 and BCJ8 showed that provision of a 300 kN axial load resulted in only 4.6 % increase in joint shear strength. Nevertheless, there were notable differences in the deformations of two joints and the inelastic column contribution was higher for BCJ8 as reported by Leon.

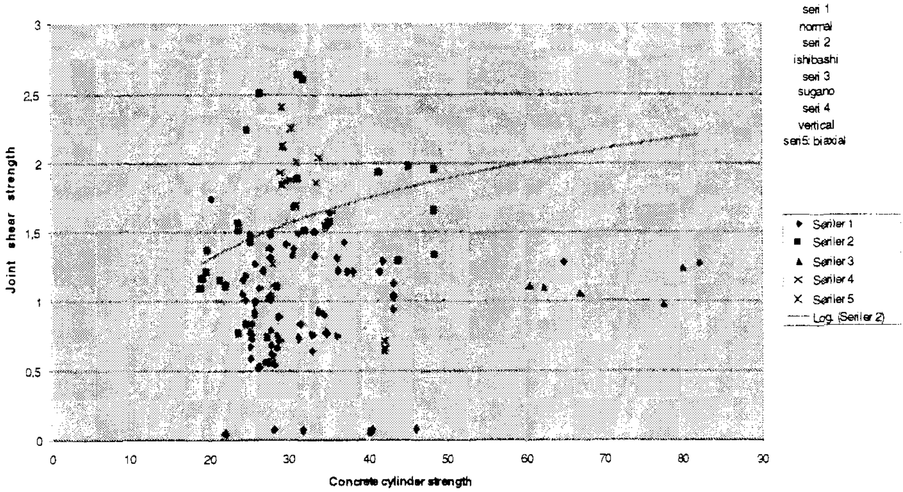

Figure 1: The influence of concrete cylinder strength on joint shear strength

2.3 The influence of joint aspect ratio

It is apparent that the direct strut mechanism is very influential in the joint shear strength. If the depth of the column is increased, while holding the beam depth constant, the column compressive rectangular stress block s width is increased consequently increasing the width of the direct strut mechanism. This way, the stress in the direct strut decreases which in turn increases the joint shear strength. The authors made a parametric study whose details are shown in Figure 3. The specimens in the experimental database had joint aspect ratios ranging from 0.9 to 1.4. Careful inspection of the Figure 3 yields the following results:

Uniaxially loaded specimens show that as the joint aspect ratio (hb/hc) increases, the average joint shear stress of the specimens decrease. The possible inconsistencies with the above mentioned trend could be due to the interaction of different parameters.

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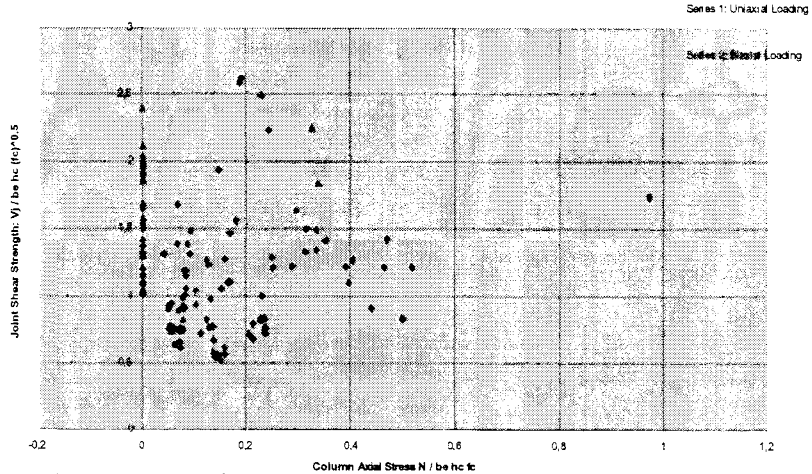

Figure 2: The influence of column axial stress on the normalized joint shear strength

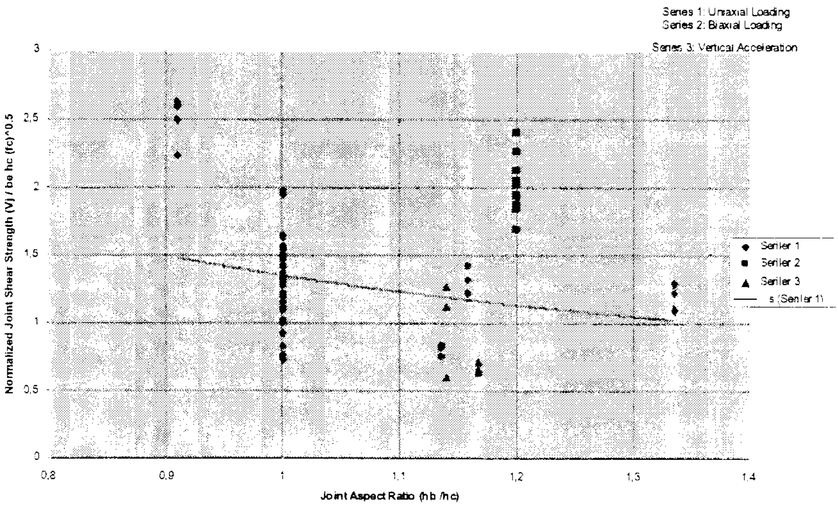

Figure 3: The influence of joint aspect ratio on the normalized joint shear strength

2.4 Inspection of the specimens with respect to the countries

The US and Japanese specimens have got relatively high average joint shear strength (1.278). The lowest average joint shear belongs to the group of New Zealand experiments. This is possibly because;

1. The New Zealand Design Procedure is not based on maximum strength.
2. The New Zealand Design Procedure stipulates very high limits for the ratio of the column height to the diameter of the beam bars. This decreases the normalized joint shear strength.

The failure modes of all the specimens in the database are evaluated as shown in Figure 4. The Figure shows that 29% of all the Japanese specimens failed in the Beam. 27% of all the Japanese specimens on the other hand failed as a combination of Beam and Shear Failure.

The majority (67%) of all the New Zealand specimens in the experimental database have all failed as a combination of beam and shear failure. Only 33% of the New Zealand Specimens failed in the beam. No anchorage failure was observed in New Zealand Specimens.

50% of the US Specimens failed as a combination of joint shear and anchorage failure. 18 % of all the specimens failed as a combination of beam, joint shear and anchorage failure. Another 18 % failed as a combination of Beam and Anchorage failure. Only 13.6 % of all the US Specimens failed in the Beam. No column failure was observed in any of the specimens in the database.

2.5 The influence of stirrups on joint shear strength

The authors plotted the stirrup ratio versus joint shear strength on Figure 5. The Figure shows no relation between the stirrup ratio and the joint shear strength. The authors are in the opinion that this is possibly because;

- The loading history is more influential than the stirrup ratio in uniaxial and cyclically loaded joints.
- Other factors such as bond dominates the behavior of cyclically loaded joints.
- Other factors such as the yield strength of the stirrups may be influential.

In order to investigate the possibility of the last factor, the authors plotted the stirrup index As fy / be hc $\sqrt{fc}$ vs the joint shear strength in Figure 6. The Figure shows much scatter in data and no apparent relation is seen.

The authors inspection of second series of tests showed that the provision of extra stirrups has not increased the joint shear strength of these specimens. BCJ7 was provided 10 # 4 ties whereas the other specimens were provided by 2 # 4 ties. It is apparent that the provision of these ties has not increased the joint shear strength of BCJ7 much. Nevertheless, Leon reports that the deformations have turned out to be more desirable mechanisms such as elastic and beam inelastic rotation.

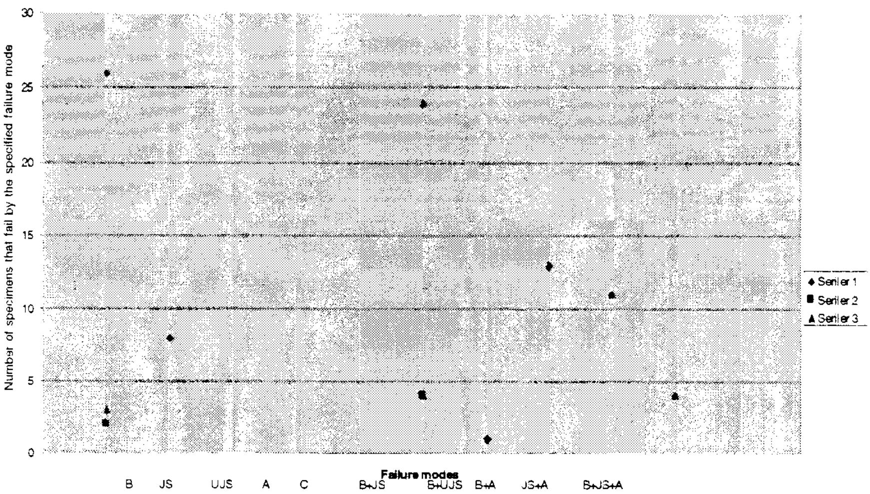

Figure 4: The failure modes by country

The authors also investigated the third series of tests . The specimen SC3 was identical to SC2 except the joint shear reinforcement provided. The transverse reinforcement ratio in SC3 is almost decreased to half of the transverse reinforcement ratio in SC2. The joint shear capacity decreases by 7.5% in SC3 compared to SC2. Nevertheless, the authors are in the opinion that this does not prove that the joint shear strength is much influenced by the increase in the transverse reinforcement. This increase may be due to other factors such as the differences in the reported and the actual concrete strengths during the test.

2.6 Loading type

The authors investigated the ordinary strength specimens SB1 and SB2 of Higazy which had identical column and beam cross sections and equal longitudinal top and bottom reinforcement as well as longitudinal column reinforcement and joint shear reinforcement. The only difference between the two specimens was that the column of SB1 was under compression while the column of SB2 was under column axial tension. The experimental data showed that SB1 had a joint shear capacity of 34.15 kips while SB2 had a joint shear capacity of 30.02 kips. It is apparent that the joint shear capacity of SB1 is 14% higher than SB2. This shows that in ordinary strength specimens, the joint shear capacity decreases 14% by the provision of 5% column axial tension. Furthermore, the high strength specimen SC1 and SC2 were also identical except that SC1 was under column axial tension while SC2 was under column axial compression. The joint shear capacity of SC1 as reported by tests was 18.2 kips while the joint shear capacity of SC2 was 20.14 kips. These figures show that the column axial tension decreases the joint shear capacity by 9.63%. It is evident that

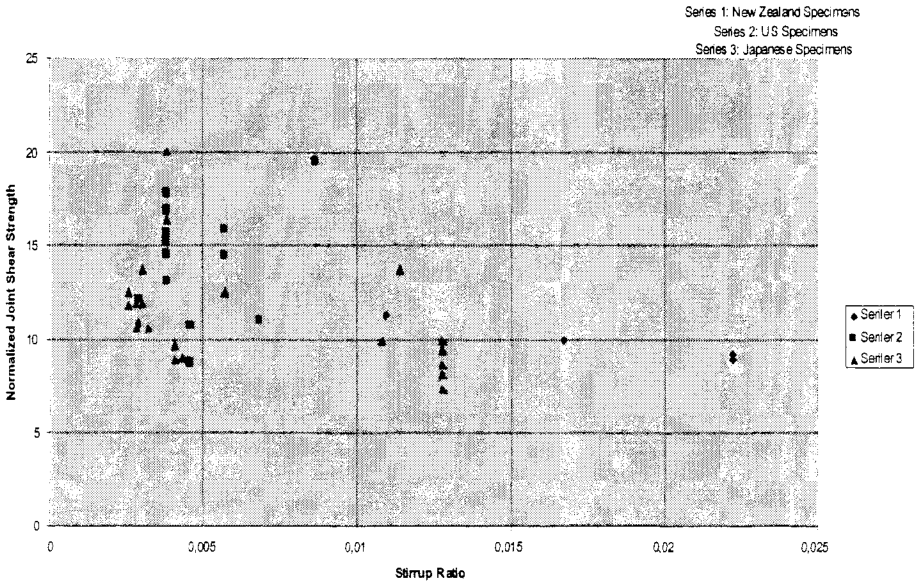

Figure 5: The influence of stirrup ratio on the normalized joint shear strength

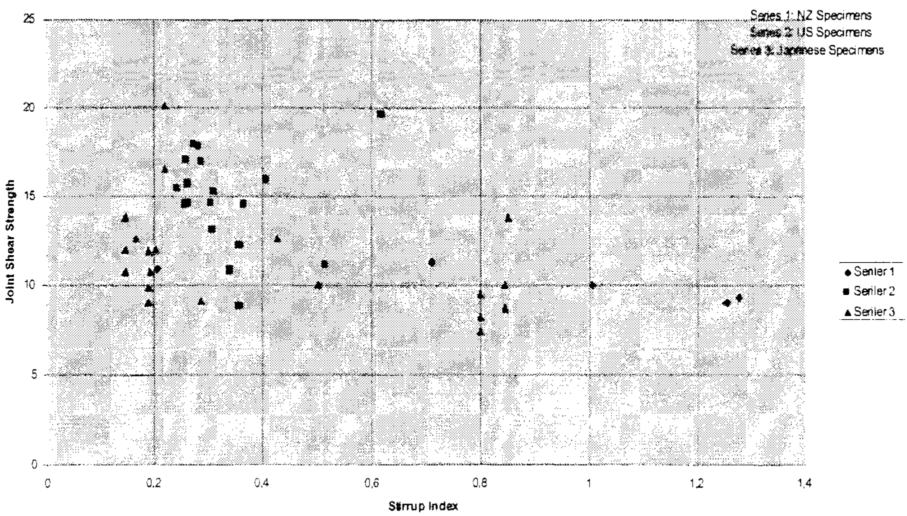

Figure 6. The influence of stirrup index on the normalized joint shear strength

the column axial tension decreases the joint shear capacity more for ordinary strength specimens (14%), compared with the high strength specimens (9.63%).

3 Conclusions

- Column axial tension decreases the joint capacity more so for ordinary strength specimens compared to high strength specimens (14% compared to 9.63%). Nevertheless, increases in the column compressive axial load does not influence the joint shear strength much.
- As the joint aspect ratio increases, the joint shear strength decreases.
- Failure modes are very influential on the joint shear strength. If bond failure occurs in the joint, the truss mechanism disappears and the strut mechanism is enhanced. This increases the joint shear strength of specimens that fail by anchorage failure with respect to the ones that fail by other failure modes.
- Neither the stirrup index nor the stirrup ratio influences the joint shear strength of cyclically loaded joints. Loading history is more influential in joint shear strength.
- Inspection of Leon s biaxially loaded tests showed that the lowest joint shear strength was in BCJ11 which had narrow beams. It is very apparent that narrow beams diminish the effectiveness of the direct strut mechanism by decreasing the breadth of the strut as reported by Leon.
- Concrete cylinder strength increases the joint shear strength.
- As a successful design is characterized by a failure mode in the beam, the authors are in the opinion that the most successful results were achieved by Japanese and New Zealand tests, as most of them failed in the beam.
- The most influential parameters influencing the joint shear strength are loading history and the bond. Joints which are loaded by more number of cycles before they reach their maximum joint shear strength have lower joint shear strengths compared to the ones that are subject to fewer cycles.

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