STEEL FIBRE REINFORCED INTERIOR BEAM-COLUMN JOINTS WITHOUT SHEAR REINFORCEMENT AND BEAM BARS PASSING THROUGH JOINT

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Summary: This paper discusses an innovative steel fibre reinforced concrete structural system, developed to streamline the works of reinforcing for R/C interior joints. In this system, beam longitudinal bars on opposite sides of interior joints are neither lapped nor connected within the joints, but provided with head anchors using steel fibre concrete. The headed bars are anchored around the middle section of the joints. Steel fibres are added to plain concrete to enhance joints’ shear strength and anchor load capacity of the headed bars without joint shear reinforcement. The effect of using steel fibres is investigated through two tests. Pull-out tests of single headed bars were carried out. And, seismic structural performance tests of the proposed interior joints are carried out. A design method of the novel structural system is also suggested. It provides sufficient satisfaction as to the interior joint test results.

1 INTRODUCTION

In general, reinforced concrete (RC) buildings need to be designed for long-term loadings, wind loadings and earthquake loadings. For each category of loadings, load magnitudes differ depending on the site areas and countries where structures are to be constructed. In case of earthquake loadings, large differences are observed between countries or even between areas of a same country. As Japan is located in a region of high seismic density, buildings should have a sufficient horizontal stiffness and horizontal capacity to sustain frequent and large earthquakes. Actually, most of buildings in Japan are made of moment-resisting frame structures. The construction of such frames raises the problem of reinforcement congestion within beam-column joints. The authors have dealt with this issue and propose a novel method for constructing joints within moment-resisting frames using steel fibres.
In general, longitudinal bars of opposite beams are extended across interior joints counting for developing bond stresses around these bars to ensure an effective anchor. Joints shear reinforcements are needed within beam-column joints to confine their core concrete. Nevertheless, beam longitudinal bars, column longitudinal bars and joints' shear reinforcements when crossed in interior joints result in a complex detailing and are sometimes difficult to arrange into tight joint cores due to lack of space. Therefore, as a solution, a streamlined RC interior joint system using steel fibre concrete is proposed. This joint does not contain any shear reinforcement within its core as shown in Fig-1 and instead it steel fibres are used to enhance joint’s shear strength as well as the anchor load capacity of the steel bars of opposite beams, which are neither lapped nor connected within the interior joint but are provided with head anchors. The headed bars are anchored around the middle section of the joint.

This paper describes the results of two research stages carried out to develop the proposed novel system. In the first research stage, the effect of adding steel fibres to plain concrete is investigated through pull-out tests of single headed bars. In the second research stage, seismic structural performance tests of the proposed interior joint are carried out and a design evaluation method is then suggested.

2 FIRST RESEARCH STAGE: PULL-OUT TEST

2.1 Test Objectives

The pull-out test was planned to investigate the effect of adding steel fibres to concrete on longitudinal headed bars of beams, where the embedded length of these bars was relatively short in comparison with ordinary reinforced concrete beam-columns joints.

2.2 Test setup

Fig-2 shows the load test setup where test specimens simulate the beam longitudinal headed bars anchored in the joints. A rigid steel beam supported by two steel mountings was set on the specimens and served to apply a pull out force on the anchored steel bars using a 500kN jack. The two steel mountings and the specimens were fixed firmly to a stiff reaction floor in order to prevent any uplift of the specimens in the pulling direction. The two steel mountings were set at a sufficient distance away from the beam longitudinal bars in order not to affect the developing mechanism and the anchorage strength. The tests were carried out by incrementing the pull-out load in one direction to induce tensile stresses on the anchored bars in a way to simulate the behaviour of beam longitudinal bars at the beam ends under earthquake loading. To allow the anchorage strength develop fully and avoid yielding of steel bars, ultra-high strength steel bars of yield strength higher than 685MPa were used. Furthermore, small size bars were used as horizontal reinforcement in the specimens in order not to affect the anchorage strength.

2.3 Test specimens

Ten specimens were constructed to perform the test. Fig-3 shows the details of the specimens and Table-1 lists the test parameters and material characteristics. The selected test variables are as follows.

<table>
<thead>
<tr>
<th>Test variable</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Steel fibre volume ratio</td>
<td>0%, 0.5%, 1.0% (as to concrete volume)</td>
</tr>
<tr>
<td>2) Concrete strength</td>
<td>f’c30, f’c60, f’c90</td>
</tr>
<tr>
<td>3) Transverse reinforcement</td>
<td>Uniformly distributed, Concentrated</td>
</tr>
<tr>
<td>4) Column longitudinal bars</td>
<td>low amount, double amount (as to the low amount)</td>
</tr>
</tbody>
</table>
Fig -2 Pull-out test setup

Fig -3 Reinforcement detail of specimens

Pull-out test specimens simulated the red square area in the joint.
The specimens S30N, S60N and S90N, which were constructed without shear reinforcement, were set to study the effect of the steel fibre concrete of different strengths. These specimens had the same steel fibre volume ratio of 1.0%. This ratio was determined based on some previous test results related to beam-column joints of the same concept as those presented herein in the second stage tests. The specimen P60N did not contain steel fibres and had a concrete strength of about 60MPa. This specimen was intended to be compared with the specimen S60N. The specimen S60G contained 0.5% volume of steel fibres. It was intended to be compared with the specimens S60N and P60N. The specimens S60E, S60I, S60U and S60H were considered for studying the influence of the shear reinforcement around beam longitudinal headed bars. The specimen S60M was aimed at studying a presumed shear transfer induced by the horizontal bars (column longitudinal bars) and the influence of these horizontal bars on the anchorage strength of beam longitudinal headed bars in steel fibre concrete beam-column joints.

### Table 1 Specimens, test variables and materials’ measured strength

<table>
<thead>
<tr>
<th>Specimens</th>
<th>Concrete</th>
<th>Steel fibre&lt;sup&gt;1)&lt;/sup&gt; Volumetric ratio</th>
<th>Shear reinf.</th>
<th>Column longi.bars</th>
<th>Detail (Fig-2)</th>
<th>Measured strength Pmax (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S30N</td>
<td>fc33.6</td>
<td>ρ = 1.0%</td>
<td>none</td>
<td></td>
<td>(a)</td>
<td>193</td>
</tr>
<tr>
<td>S60N</td>
<td>fc65.7</td>
<td>ρ = 1.0%</td>
<td></td>
<td>2-D13</td>
<td>(b)</td>
<td>328</td>
</tr>
<tr>
<td>S60G</td>
<td>fc64.0</td>
<td>ρ = 0.5%</td>
<td></td>
<td></td>
<td>(c)</td>
<td>199</td>
</tr>
<tr>
<td>S60E</td>
<td>fc65.7</td>
<td>ρ = 1.0%</td>
<td>2-D6@80</td>
<td></td>
<td>(d)</td>
<td>424</td>
</tr>
<tr>
<td>S60I</td>
<td>fc65.7</td>
<td>ρ = 0%</td>
<td>Both side Intensive</td>
<td>(e)</td>
<td></td>
<td>424</td>
</tr>
<tr>
<td>S60U</td>
<td>fc65.7</td>
<td>ρ = 0%</td>
<td>One side intensive</td>
<td>(f)</td>
<td></td>
<td>325</td>
</tr>
<tr>
<td>S60H</td>
<td>fc65.7</td>
<td>ρ = 0%</td>
<td>High-strength</td>
<td>(g)</td>
<td></td>
<td>315</td>
</tr>
<tr>
<td>S60M</td>
<td>fc65.7</td>
<td>ρ = 0%</td>
<td>One side intensive</td>
<td>(h)</td>
<td></td>
<td>414</td>
</tr>
</tbody>
</table>

Property of steel bars:

- D25 USD685, Yield strength fy=720MPa, Modulus of elasticity Es=1.98 × 10<sup>5</sup>MPa
- D13 SD490, Yield strength fy=480MPa, Modulus of elasticity Es=1.88 × 10<sup>5</sup>MPa
- D6 USD685, Yield strength fy=575MPa, Modulus of elasticity Es=1.99 × 10<sup>5</sup>MPa
- D6 SD345, Yield strength fy=367MPa, Modulus of elasticity Es=1.81 × 10<sup>5</sup>MPa

Steel fibre:

- Length 31mm, Diameter 0.6mm
- Aspect ratio 51.7
- Tensile strength more than 1000MPa

The specimens S30N, S60N and S90N, which were constructed without shear reinforcement, were set to study the effect of the steel fibre concrete of different strengths. These specimens had the same steel fibre volume ratio of 1.0%. This ratio was determined based on some previous test results related to beam-column joints of the same concept as those presented herein in the second stage tests. The specimen P60N did not contain steel fibres and had a concrete strength of about 60MPa. This specimen was intended to be compared with the specimen S60N. The specimen S60G contained 0.5% volume of steel fibres. It was intended to be compared with the specimens S60N and P60N. The specimens S60E, S60I, S60U and S60H were considered for studying the influence of the shear reinforcement around beam longitudinal headed bars. The specimen S60M was aimed at studying a presumed shear transfer induced by the horizontal bars (column longitudinal bars) and the influence of these horizontal bars on the anchorage strength of beam longitudinal headed bars in steel fibre concrete beam-column joints.

#### 2.4 Test results

Fig.4 shows the pull-out load test results in terms of the measured pull-out force and steel bar’s pull-out displacement at the concrete surface. The measured steel bar’s pull-out displacement at concrete surface is illustrated in Fig-4(f). For an easy comparison, the test results in Fig-4 are grouped for each variable factor. Fig-5 shows the final appearance of the representative specimens.

All specimens showed a cone-shaped failure without yielding of the beam longitudinal bars. While the specimens S30N, S60N, S90N and S60G, which have no shear reinforcement around their beam longitudinal bars, showed an abrupt failure and reached their maximum strengths when cone-shaped crack occurred, the specimens S60I and S60S showed a ductile behaviour after the occurrence of the cone-shaped crack, due to the resistance developed by shear reinforcement beyond cracking.

(a) Concrete strength

(b) Volumetric ratio of steel fibre

(c) Shear reinforcement

(d) Yield strength of shear reinforcement

(e) Amount of the horizontal bars

(f) Measurements of the test

Fig-4 Test results and Measurement
For the same steel fibre volume ratio, higher anchorage strength was obtained, as shown in Fig-4(a), for higher concrete strength. Nevertheless, the increasing rate of the anchorage strength was not proportional to the increasing rate of concrete strength.

For the same concrete strength, higher anchorage strength was obtained, as shown in Fig-4(b), for higher steel fibre volume ratio. The test results showed a linear relationship between the anchorage strength and the volume ratio of steel fibres.

The presence of shear reinforcement around the longitudinal headed bars was effective for the anchorage strength. Relatively to their amount, shear reinforcement increased the anchorage strength and induced high ductility, as shown in Fig-4(c). Furthermore, the test results, shown in Fig-4(d), revealed that the effective concrete strength of the steel fibre concrete should be taken into account when using high-yield strength shear reinforcement.

The amount of horizontal bars reflecting column longitudinal bars in beam column joints influenced the anchorage strength of beam longitudinal headed bars as shown in Fig-4(e). As observed in the test, the horizontal bars were crossed by the cone-shaped crack. The reaction of these horizontal bars restrained the deformation of the cone-shaped block and consequently increased the anchorage strength of beam longitudinal headed bars. Nevertheless, this effect has been ignored in the existing design equations.

2.5 Review of the pull-out test results

The main findings of the pull-out test are summarized in Fig-6 and Fig-7. Fig-6 shows the effect of concrete strength on the anchorage strength of the tested headed bars embedded in the steel fibre concrete specimens. The anchorage strength of the beam longitudinal headed bars in beam column joints using a volume ratio of 1.0% of steel fibres is proportional to that of 0.5% and to that without steel fibres. Fig-7 shows the effect of steel fibre volume ratio on the anchorage strength of specimens having similar concrete strengths. The vertical axis represents the anchorage strength ratio $\alpha$, which is the anchorage strength normalized to that of the specimen P60N without steel fibres. Fig-7 also shows a lower approximation for the anchorage strength ratio, where it predicts in the case of 1.0% steel fibre concrete an anchorage performance of more than 1.5 times that of plain concrete.
3 BEAM-COLUMN JOINTS TEST

3.1 TEST OBJECTIVES

This experimental study was carried out for the following two main objectives.

1) To deepen the understanding of the basic structural performance of steel fibre reinforced interior beam-column joints without shear reinforcement and beam bars passing through joint as shown Fig-1.
2) To find out the stress transfer mechanism in the joints with considered effect of steel fibre concrete using the anchorage test results.

3.2 Test specimens

To accomplish these objectives, it was necessary to obtain different failure mode of the joints. The design specimens were based on previous research[1], which treated the similar beam column joints using plain concrete. Two specimens, half size of the intended actual elements, were prefabricated in a similar way as in the actual case and then tested as shown Table-1 and Fig-8. They were designed according to the results of the previous research and also by taking into account the pull-out load test results. The material characteristics as well as the design parameters are given in Table 1.

The specimen No.1, designated as “Design standard”, was similate the actual beam column joints and was expected to occur flexural yielding of beam longitudinal bars without joint shear failure. No. 1’s beam longitudinal bars used grade SD390 of which yielding stress is more than 390MPa.

The specimen No.2 was designed to experience a joint shear failure by using high strength steel (SD490) for its beam longitudinal bars. While the tensile reinforcement ratio of this specimen was 1.64 times that of the specimen No.1 to increase the joint shear stress, other details were similar.

The major feature of these specimens was that their beam longitudinal bars were not passing through the joints but were embedded around the middle section of the joints. These bars were provided with mechanical anchors, so-called headed bars. Fig-9 shows the structural work method of the joints using the actual frames. Firstly, the precast beams were set up as shown Fig-9(a). Secondly, the joints are casting steel fibre concrete as shown Fig-9(b). Finally, the upper columns were assembled with the joints and with the lower columns by injecting a non-shrinking mortar, respectively, into the gaps and into the splice grout sleeves to ensure an adequate splicing of the columns’ longitudinal bars.
Table -3 Description of test specimens

<table>
<thead>
<tr>
<th>Specimen</th>
<th>No.1</th>
<th>No.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>key-word</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Joints</td>
<td>Concrete strength, f'c (second modulus : Ec)</td>
<td>Steel Fiber concrete 75.3 (3.89×10^6 MPa)^1</td>
</tr>
<tr>
<td></td>
<td>First upper and bottom shear reinforcement (Grade)</td>
<td>2-D6 (SD685)^2</td>
</tr>
<tr>
<td>Beam</td>
<td>Section : B×D [mm]</td>
<td>225×450</td>
</tr>
<tr>
<td></td>
<td>Concrete strength, f'c (second modulus : Ec)</td>
<td>Plain concrete 38.4 (3.05×10^6 MPa)</td>
</tr>
<tr>
<td></td>
<td>Longitudinal Bars (Grade), [pt]</td>
<td>4 + 2 – D16 (SD390)^3 [1.34%]</td>
</tr>
<tr>
<td></td>
<td>Shear reinforcement (Grade), [pw]</td>
<td>2 – D6@60 (SD685)^1, 0.47%</td>
</tr>
<tr>
<td>Column</td>
<td>Section : B×D [mm]</td>
<td>400×400</td>
</tr>
<tr>
<td></td>
<td>Concrete strength, f'c (second modulus : Ec)</td>
<td>Plain concrete 38.4 (3.05×10^6 MPa)</td>
</tr>
<tr>
<td></td>
<td>Longitudinal Bars (Grade), [pt]</td>
<td>12 – D19 (SD490)^5 [1.91%]</td>
</tr>
<tr>
<td></td>
<td>Shear reinforcement (Grade), [pw]</td>
<td>4 – D6@60 (SD685)^2, 0.53%</td>
</tr>
</tbody>
</table>

Notation
- pt: tensile reinforcement ratio, pw: shear reinforcement ratio
- Steel bars information Cross-sectional Area D22: 387.1 mm^2, D16: 199 mm^2, D6: 32 mm^2
- *1 Steel fibre volume ratio ϕ = 1.0%.
- *2 Yield strength f_y=757 MPa, Modulus of elasticity Es=1.99×10^6 MPa
- *3 Yield strength f_y=448 MPa, Modulus of elasticity Es=1.93×10^6 MPa
- *4 Yield strength f_y=522 MPa, Modulus of elasticity Es=1.94×10^6 MPa
- *5 Yield strength f_y=496 MPa, Modulus of elasticity Es=2.03×10^6 MPa
3.3 Test setup

The loading was applied vertically at the tips of the beams while the displacement of the columns' supports was restrained laterally at both ends and vertically at the bottom end of the columns. The axial loading was applied at the top of the columns, with a constant axial force ratio of 0.15 during the test. The specimens were tested in a displacement control mode, in which the joints were subjected to two cycles of the following increasing amplitudes of the story drift angles, \( R = 1, 2, 3.3, 5, (2), 7.5, 10, (5), 15, 20, (5), 30, 40 \) and \( 50 \times 10^{-3} \) rad. Short amplitudes were inserted (numbers in parenthesis) in the loading protocol to simulate the effect of actual earthquake loadings. The second cycle relative to each amplitude of the story drift angle was used to evaluate the equivalent viscous damping factor, \( h_{eq} \).

3.4 Results of experiment

Fig-10 shows the relationships of story shear force to interior story drift angle as well as the equivalent viscous damping factor, \( h_{eq} \). The main observation recorded and calculated beam flexural yielding strength, \( \text{calVby} \), according to AIJ1999 equation\(^\text{2}\) is illustrated in each figure. Fig-11 shows the cracking pattern at \( R = 20 \times 10^{-3}, \ 50 \times 10^{-3} \) rad. The specimens were painted white and the main reinforcements were sketched on the concrete surface before testing. The cracks were marked with felt-tip pens only to the right-hand side surface of the specimens to show clearly the crack pattern. The left-hand side surface was not marked with felt-tip pens to avoid any magnification of crack widths due to felt-tip pen lines.

The beam longitudinal bars of the specimens No.1 reached their yielding strength level at the story drift angle \( R = 5.9 \times 10^{-3} \) rad and then plastic hinges formed at the ends of the beams at the cycle of \( R = 7.5 \times 10^{-3} \) rad, owing to the radiating cracks developed under cyclic loadings without joint shear failure. Afterwards, the story shear force decreased beyond \( R = 50 \times 10^{-3} \) rad after beams yielding due to the sliding shear failure at the beam ends. The equivalent viscous damping factor was around 3.0% until \( R = 5.0 \times 10^{-3} \) rad before beams yielding and increased after beams yielding.

The beam flexural strength of specimens No.2 did not reach the calculated value. The specimens showed a maximum strength at \( R = 20 \times 10^{-3} \) rad. The crack width around beam longitudinal headed bars, increased after \( R = 7.5 \times 10^{-3} \) rad due to the anchorage reaction stress. After \( R = 20 \times 10^{-3} \) rad the story shear force decreased and then joint shear failure occurred.

3.5 Analysis of the test results

Both specimens experienced the cracks around their headed bars in the joint due to the growing reaction forces at headed anchors. These reaction forces were caused by the developed tensile stress in the beam longitudinal bars under the simulated seismic loading. Crack width in the specimens No.1 did not increase at around or even after flexural yielding level until sliding shear failure occurred at the end of the beams. By means of steel fibre concrete, specimens No.1 was able to transfer the joint shear stress without passing through beam longitudinal bars. Contrary to the specimen No.1, crack widths in the specimen No.2 increased with increasing story drift angle until joint shear failure occurred as shown Fig-11. Large cracks occurred from headed anchors location to opposite compression area of the joint and expanded through the core area of the joints. Furthermore, other cracks occurred along the diametrically opposed beam ends' compression areas. In other words, double main compressive struts formed in this beam column joints when reaching the joint shear failure level.

4 PROPOSED DESIGN EQUATION

The two test of this research has highlighted the benefit of steel fibre concrete and the feasibility of the proposed beam column joints. The test of two beam column joints exhibited the mechanism of the steel fibre reinforced interior beam column joints without shear reinforcement and beam longitudinal
bars passing through the joints. The mechanism is illustrated in Fig-12. Under a seismic load, the resulting moments and shear forces of beams and columns acted as external loading on the joint. The stresses of diametrically opposed compression areas as well as the reaction force of the beam
longitudinal headed bars are mutually balanced. Because beam longitudinal bars are not passing through the joints, a second compressive strut arises between the beam longitudinal anchors and the compressive area at beam ends. This concept added to previous research results \cite{1} reached the shear design model for the proposed beam column joints outlined as follows.

The joint shear strength using the double strut model (refer to Fig-12 and Fig-13)

\[ V_{ju} = \min(Ts, \phi D_1 \cos \theta_1) + \phi D_2 \cos \theta_2 \]  

Anchorage strength of beam longitudinal headed bars

\[ Ts = 0.7A_w \cdot \sigma_{wy} + \sum A_s \cdot \sigma_f \]  

Strut shape size and strength

\[ a_s = \sqrt{a_b^2 + a_c^2}, \quad a_c = 0.25h_c, \quad a_b = 0.25h_b, \quad a_s1 = a_s + a_s2 \]

\[ a_s1 = a_s \cdot \frac{T_{1 \text{ max}}}{T_{1 \text{ max}} + T_{2 \text{ max}}}, \quad a_s2 = a_s \cdot \frac{T_{2 \text{ max}}}{T_{1 \text{ max}} + T_{2 \text{ max}}} \]

\[ T_{1 \text{ max}} = \frac{\sigma_d}{2} \sin 2\theta_1, \quad T_{2 \text{ max}} = \frac{\sigma_d}{2} \sin 2\theta_2 \]

\[ \theta_1 = \tan^{-1} \left( \frac{h_b}{h_c} \right), \quad \theta_2 = \tan^{-1} \left( \frac{h_b}{h_c} \right) \]

\[ \phi: \text{Strength reduction factor} (=0.85) \]

\[ A_{str1}, A_{str2}: \text{Width of strut1 and strut2}, \quad b_s: \text{Depth of strut1 and strut2} \]

\[ \sigma_f: \text{yielding strength of shear rein. in 45 degree projected from headed bars} \]

\[ a_c, a_b: \text{the distance from the neutral axis of column, beam} \]

\[ a_s1, a_s2: \text{Depth of strut1, strut2 (refer to Fig-12),} \]

\[ h_c, h_b: \text{Column depth, beam depth} \]

\[ \sigma_B: \text{concrete strength using circular cylinder (MPa)} \]

\[ \nu: \text{concrete effective factor (CEB1990)} \]

\[ \theta_1, \theta_2: \text{Angle of the strut1 and strut2 (refer to Fig-11)} \]

\[ \alpha_{sf}: \text{steel fibre reinforced factor} (=1.0 + 0.5 \cdot \rho_{sf} = 1.5) \]

\[ \rho_{sf}: \text{Volumetric ratio of steel fibre to concrete volume (=1.0%)} \]

The calculated joint shear strength of specimens No.1 and No.2 using the above equations were 1.43 and 0.76 times of the calculated joint shear force assumed beams flexural yielding at beam ends. Although the number of the data is restricted, the availability of the double strut model was confirmed this research and previous research \cite{1} data using plain concrete using similar joints.
5 CONCLUSIONS

In this research program, the seismic structural performance of the steel fibre reinforced interior beam column joints without shear reinforcement and beam longitudinal bar passing through was investigated. The following conclusions have been found.

1) Steel fibre reinforced concrete is effective to improve the performance of anchorage strength despite of the short anchorage length. The reinforcing effect was proportional to volume ratio of steel fibres to concrete volume.

2) Anchorage strength increase directly with concrete strength elevated to the power 0.5 for a range of concrete strength from $f'c33$ to $f'c83$.

3) Use of steel fibre concrete for beam column joints allowed a good performance of the innovative joints in which beam longitudinal bars are provided with headed anchors and do not need to pass through the joint. The proposed double strut model is able to design the innovative joints and evaluate properly failure mode.

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