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# DIAGONAL TRANSFER CAPACITY OF COMPRESSIVE FORCE IN CONCRETE OF R/C COLUMNS

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## SUMMARY

This paper presents the experimental investigation of diagonal transfer capacity of compressive force in concrete of R/C columns subjected to combined compression, bending, and shear. It is necessary to estimate flexural strength, shear strength, and shear cracking stress of the column accurately in shear design in order to control the failure mode of the column during a strong earthquake. Diagonal transferred compressive force is important element for that, and is aimed in this paper. R/C column specimens were tested for estimation of the flexural strength, the shear strength, and the shear cracking strength. Sixty-five column specimens were tested for the estimation of flexural strength. Main parameters of the test were cross section, axial force history, concrete strength, shear span ratio, and arrangement of main reinforcement. An equivalent rectangular stress distribution is assumed to calculate the concrete stress. The test results indicated that the maximum stress value factor, kmax, of the stress block under combined compression, bending and shear is approximately 1.35 times larger than that under combined compression and bending. It seemed that other than loading combination which is mentioned earlier the parameters employed in this study had insignificant effect on the stress value of stress block. On the other hand, twenty-six column specimens were tested for the estimation of shear strength and shear cracking stress. To make the transfer of stress in concrete simple, shear reinforcements were removed from the specimens. Parameters of the test are shear span ratio, concrete strength, and loading history. Arch mechanism was assumed in the columns to calculate shear cracking stress and shear strength. It was found that shear cracking stress can be calculated by assuming biaxial shear cracking criterion, and the upper bound and the lower bound of shear strength can be estimated by decreasing rates of arch strength decided by arch solution.

## INTRODUCTION

In order to control the failure mode of R/C column during a strong earthquake, the flexural strength of the critical section, the shear strength, and the shear cracking stress of the column should be accurately estimated. Diagonal transferred compressive force is important element for that. In case of the failure of R/C column under compression, bending, and shear, it can be said that the compressive force transfers diagonally in concrete. As it was made clear by the paper written by E.Hognestad in 1951[4] , the basic behavior of R/C members subject to combined bending and axial load has been used for a long time to estimate the flexural strength of R/C columns, as ACI Building Code [1] . In flexural design, the flexural strength of R/C columns is generally based on lower bound approximations obtained from classical experiments, which is evaluated safe side. However, in shear design, the actual maximum shear force may be higher than that calculated from the lower bound approximation due to the underestimation. Therefore, in order to minimize the possibility of shear failure, the upper and lower limits of flexural strength should be accurately estimated. On the other hand, shear strength is calculated by assuming truss mechanism and arch mechanism in "Design Guidelines for Earthquake Resistant Reinforced Concrete Buildings Based on Ultimate Strength Concepts" edited by Architectural Institute of Japan [2]. But behavior of ultimate shear stress in concrete is very complex, and shear stress transfer in R/C columns is not clear. Accordingly, it is necessary to make shear stress transfer mechanism clear to estimate shear strength and shear cracking stress accurately. In this paper, compressive properties of concrete and shear stress transfer

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mechanism of concrete of R/C columns are investigate experimentally, and accurate expression for the estimation of flexural strength, shear strength, and shear cracking stress in shear design is developed.

Compressive properties of concrete around the critical section of R/C columns is one of the most fundamental element of the calculation of flexural strength, especially when it is much affected by compressive properties of concrete. For instance, it is when the axial force ratio of the column is more than 0.4 in the design of the building over the height of 100m. The experimental investigation based on the test results of sixty-five R/C column specimens subject to concentric compression, antisymmetric eccentric compression, symmetric eccentric compression, compression-bending, and compression-bending-shear, is presented in the section 2.

Twenty-six specimens of R/C column specimens were tested under the combined compression, bending and shear for the studies of shear stress transfer mechanism to estimate shear cracking stress and shear strength. The shear cracking stress is shear stress when first shear crack appears. Parameters of the test are shear span ratio, concrete strength, and loading history. It can be consider that behavior of ultimate shear stress in concrete is very complex because of combined arch mechanism and truss mechanism. Accordingly, truss mechanism was removed from the specimens to make compressive force transfer in the concrete simple. Therefore all the twenty-six specimens have no shear reinforcements, and main reinforcements has no bond. Based on the test results, shear cracking stress and shear strength were estimated by assuming arch mechanism in the columns. A study of shear stress transfer is presented in the section 3.

## INVESTIGTION OF COMPRESSIVE PROPERTIES OF CONCRETEAROUND THE CRITICAL SECTION OF R/C COLUMNS

### Experimental Program:

Sixty-five R/C column specimens of nearly 1:5 scale model were tested for study of compression properties of concrete around the critical section. Table 1 provides a summary of details of test specimens. The concrete strength of the columns varied from 30MPa to 60MPa, also the length were varied from 250mm to 1000mm. Cross sectional examples of test specimens are shown in Figure 1. An example of specimen is shown in Figure 2. Mechanical properties of reinforcement are shown in Table 2. Three different arrangements of reinforcement, consisting of PC bars and deformed bars were used. The PC bar was covered with paraffin wax to remove the bond of main reinforcement [6]. For the purpose of evaluating compressive properties of concrete more clearly, some shapes of shear reinforcements were designed not to confine the concrete. The spacing was decided on the basis of preventing shear failure to take place.

**Table 1: Details of test specimens**

| Specimen designation | Section B×D(mm) | Length of specimen (mm) | Shear reinf. Pw (%) | Main reinf. | | Axial force condition* | Applied forces** | Compressive strength of concrete $\sigma_B$ (MPa) |
|---|---|---|---|---|---|---|---|---|
| CN-375-20 | 200×200 | 375 | 1.5 | 4-D13 | | Increase | C | 34 |
| RC-L750-PC13 | 150×250 | 750 | 0.63 | 4-PC bar 13φ | | Increase | ABC | 31 |
| RC-CR-375-PC13 | | 375 | 0.75 | | | Increase | SE | 33 |
| CRS-1050-H-S | | 1050 | 1.51 | 4-D13 | | Increase | ABC | [illegible] |
| CB-H-03 | 100×200 | 1050 | 1.11 | 2-D13 | | Const(0.3) | CB | [illegible] |
| CBS-N-40 | | 750 | | | | Decrease | CBS | 34 |
| CB-15-C | | 750 | | | | Increase | CB | 33 |
| CBS-15-500 | | 500 | | | | Const(0.18) | CBS | [illegible] |
| CB-C-C | 150×210 | 750 | 1.26 | 4-D13 | | Const(0.5) | CB | 32 |

*Axial force condition: { Increase; Decrease; Const.(axial force ratio) with increase of bending moment

**Applied forces: C:Compression; ABC:Antisymmetric Eccentric Compression; SEC:Symmetric Eccentric Compression; CBS:Compression and Bending-Shear; CB:Compression and Bending

The loading setup for compressive test, compression-bending test, and compression-bending-shear test, are illustrated in Figure 3. The number of specimens prepared for the test shown in Figure 3 (a), (b), (c), (d), and (e), was 5,16, 6, 20, and 18, respectively. The loading histories are divided into five types. In antisymmetric eccentric compression test and symmetric eccentric compression test, axial load was increased with bending moment. While in compression-bending test and compression-bending-shear test, with the increase of bending moment, axial load was decreased, kept constant, and kept constant then increased or decreased after bending or shear bending condition. The specimen such as CB-C-C in Table 1 was loaded under constant axial load while simultaneously loaded under 3 cycled followed by monotonic lateral load until their failure. Basically, this paper compares compressive properties of concrete around the critical section of R/C columns subject to five types of loading shown in Figure 3. The external force was applied by oil jacks, and measured by load cell. The end rotation and axial deformation were measured by displacement transducer. The strain of the main reinforcement

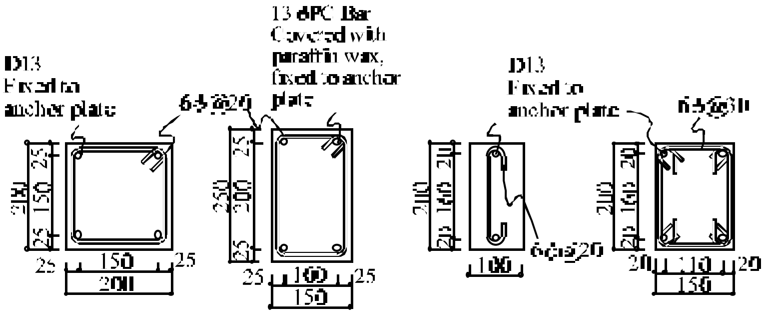



**Figure 1: Cross sectional examples of specimens**

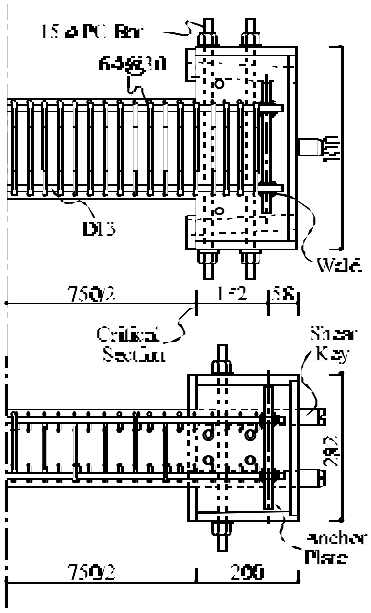
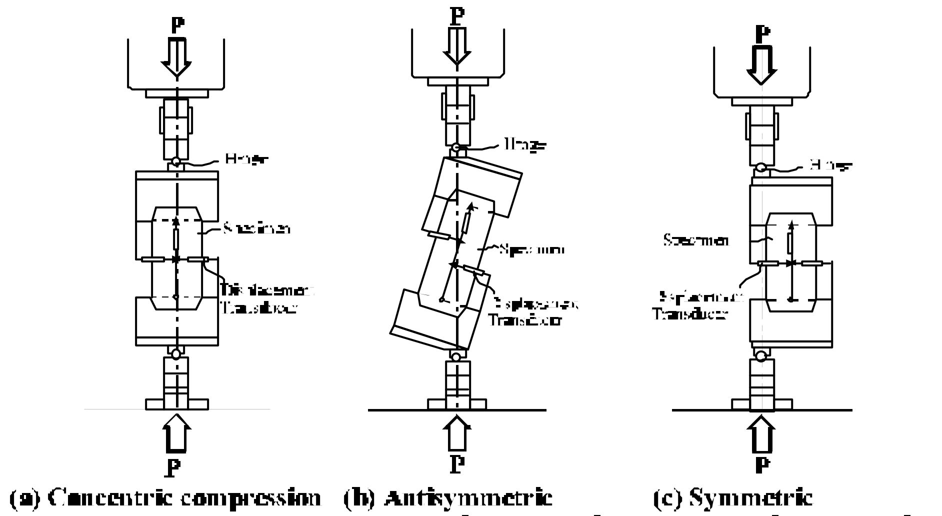


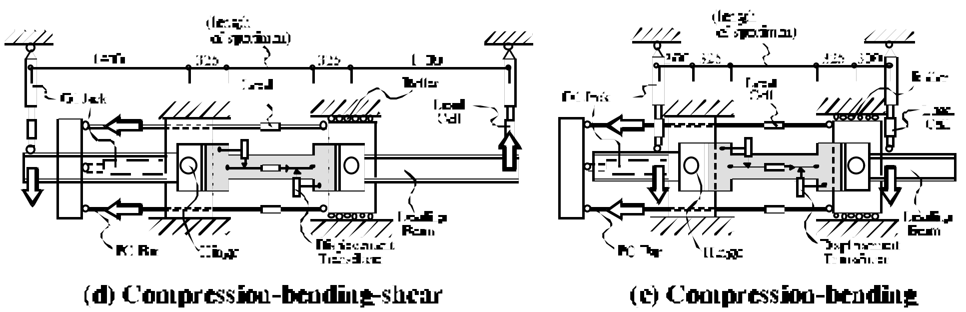

**Figure 2: An example of specimen**

**Table 2: Mechanical properties of reinforcements**

| | Main Reinforcement [illegible] | Main Reinforcement [illegible] | Shear Reinforcement [illegible] |
|---|---|---|---|
| Nominal Diameter (mm) | 12.7 | 13 | [illegible] |
| Actual Diameter (mm) | - | 13 | [illegible] |
| Yield Strength (N/mm²) | [illegible] | [illegible] | [illegible] |
| Ultimate Strength (N/mm²) | [illegible] | - | [illegible] |
| Young's Modulus (kN/mm²) | [illegible] | [illegible] | [illegible] |
| Classification of Test Piece (JIS Z2241) | No.2 | No.2 | No.2 |




**(a) Concentric compression** **(b) Antisymmetric eccentric compression** **(c) Symmetric eccentric compression**




**(d) Compression-bending-shear** **(e) Compression-bending**

**Figure 3: Loading setup**

was measured by strain gauges attached to around the critical section of the column. The stress of the main reinforcement was calculated based on the results of material tests. In cyclic loading, the strain was controlled within the elastic region, so that the Bauschinger effect in the stress-strain relationship is negligible.

**Test Results:**

Figure 4 shows representative test results. An axial load-deformation relationship of the concentric compression test is shown in Figure 4 (a). The load-end rotation relationships of the antisymmetric eccentric compression and symmetric eccentric compression tests are shown in Figure 4 (b) and (c), respectively. The end-moment and end-rotation relationships of the compression-bending-shear (CBS) and compression-bending (CB) tests are shown in Figure 4 (d), (e), and (e'), respectively. The critical sections of the specimen are at the end of the column for CBS tests, and the center for CB tests.

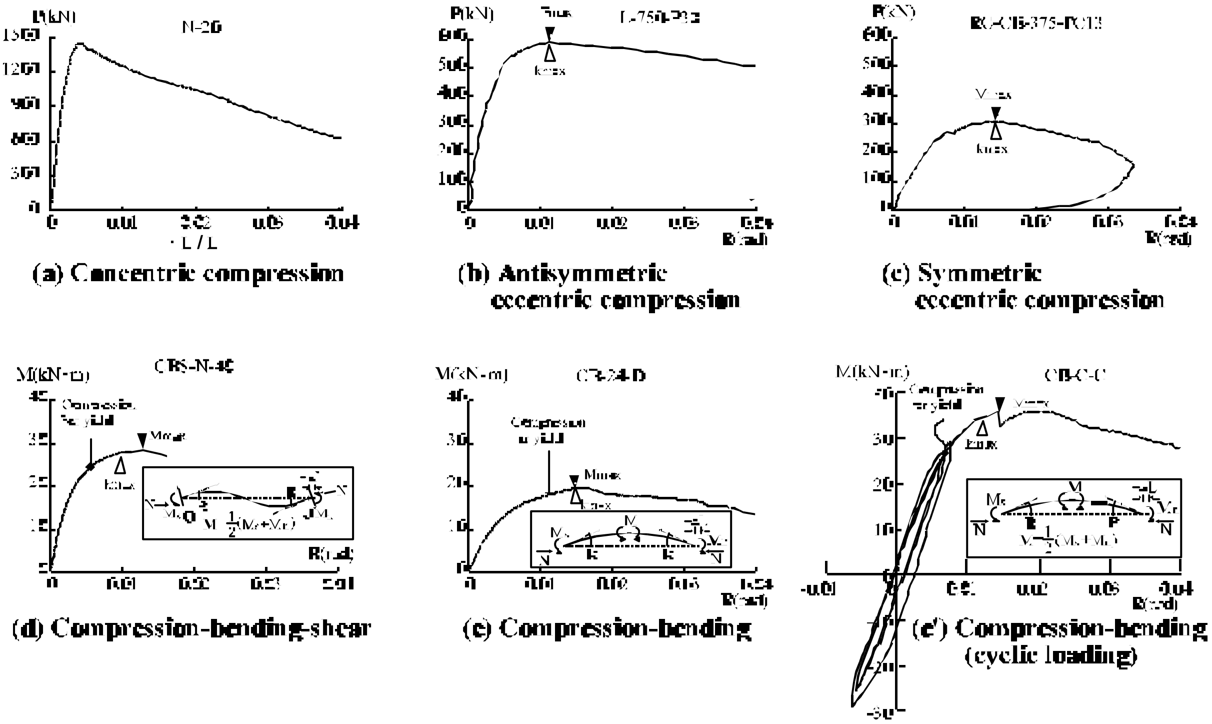



**Figure 4: Test results (loading-deformation relationship)**

**Stress Value of Stress Block on the Assumption of Equivalent Rectangular Distribution:**

Here, the stress value of stress block was calculated on the assumption of equivalent rectangular distribution of the stress of concrete, as shown in Figure 5. The moment and compressive force of concrete, Mc and Nc, were calculated as the difference between the external force of specimen loaded by oil jacks and the internal force of the main reinforcement measured by strain gauges. The stress value factor k was calculated from the equilibrium of force and moment of concrete. The maximum value of the stress value factor kmax is shown in Figure 6. As a whole, kmax value of the specimen subject to compression-bending-shear was approximately 1.35 times larger than that subject to compression-bending. The difference of length of specimen had insignificant effect on the value, as shown in Figure 6. It also can be observed that the difference of kmax value due to the other parameters investigated in this paper is inconclusive. Figure 7 shows the normalized Mc-Nc interaction curve and the experimental results of all specimens at the maximum value of the stress value factor (kmax). The interaction curves were parabolas, based on the assumption of equivalent rectangular distribution, as shown in Figure 5. The solid and void circle stand for the results of specimen subject to compression-bending-shear, and compression-bending, respectively. The void triangle stands for the results of concentric compression tests. The results of compression-bending (CB) tests were lied within the interaction curve when k is 0.85, which has been used in ACI Building Code. On the other hand, most of the results of compression-bending-shear (CBS) tests are outside of this curve. They were lied within the curve when k is 1.3. It is likely due to the confined effect by the stub especially in CBS, because the critical section is at the end of the column in CBS, while it is the center in CB. This difference is relatively small in the area where the axial force ratio is up to 0.3. However, it can be said that when the axial force ratio is more than 0.4, the difference of test results between CB and CBS becomes larger.

Therefore, in order to minimize possibility of shear failure, it is necessary to be careful of these difference in calculating the flexural strength of R/C column for shear design.

**Design Recommendations of the Flexural Strength of R/C Columns for Shear Design:**

Figure 8 shows the normalized Mc-Nc interaction for the evaluation of flexural strength of R/C columns for shear design and flexural design. It is the proposal of this paper that the flexural strength of R/C columns for shear design should be estimated by this interaction, which is designed based on the experimental results of this paper, especially the specimens subject to combined compression, bending, and shear, as shown in Figure 7. The intersection point A in Figure 8 was determined based on a parabola when the stress value factor k was 1.35, and the line of Nc/Mc = 4/D, which was through the top of parabola using k was 1.0. Then a line was determined to connect the point A and the result of concentric compression test, where normalized Nc and Mc are 0.85 and 0.

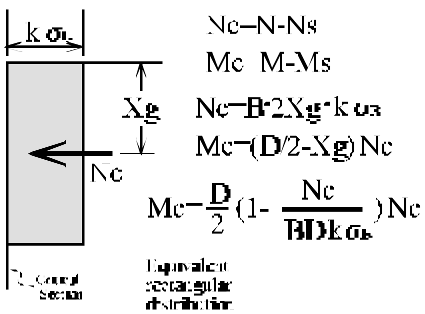


**Figure 5: Calculation og stress value of stress block**

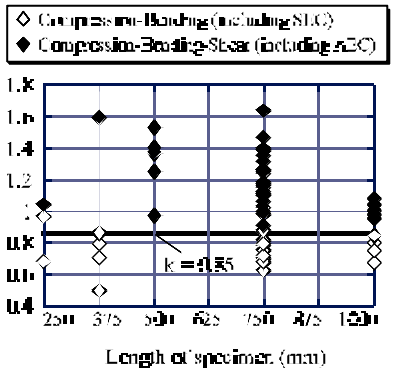



**Figure 6: kmax value**

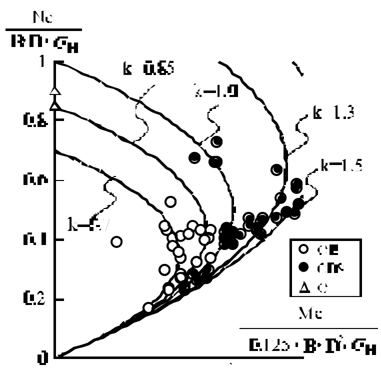


**Figure 7: Normalized Mc-Nc interaction of test results**

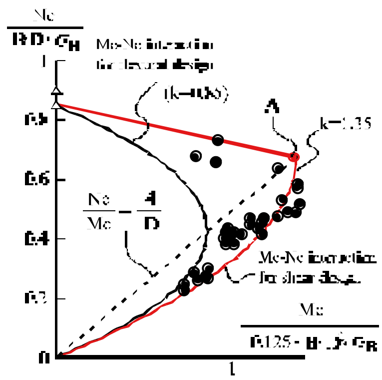


**Figure 8: Proposed Mc-Nc interaction**

## INVESTIGATION OF SHEAR STRESS TRANSFER MECHANISM OF R/C COLUMNS

**Experimental Program:**

Twenty-six specimens of R/C columns were tested for study of shear stress transfer mechanism. The specimens are different from normal R/C columns at the following three points. First the specimens have no shear reinforcements for removing truss mechanism, second the main reinforcements have no bond to cut off the stress transfer between the main reinforcements and the concrete, third high-strength bars are used for the main reinforcements not to be able to yield under ultimate condition. The purpose of first and second points are to make stress transfer in concrete simple, while third one is to calculate stress in concrete exactly. Table 3 shows dimensions of all the specimens and mechanical properties of concrete. The name of specimen is composed as followed [N or H; normal-strength concrete or high-strength concrete]-[clear length (mm)]-[A or C; test A or test C]. Examples of specimens are shown in Figure 9. All of the specimens of R/C columns were tested by two loading methods under the combined compression, bending and shear. One method is antisymmetric eccentric axial loading, as shown in Figure 3 (b). The other is compression-bending-shear test under a constant axial load, as shown in Figure 3 (d). In this chapter, we named these two methods test A and test C, respectively. Parameters in this investigation are shear span ratio and concrete strength. Two different concrete strength, normal-strength (Fc=30MPa) and high-strength (Fc=60Mpa), were used. The specimens made with normal-

**Table 3: List of specimens and mechanical properties of concrete**

| | | Name of Specimen | Section b×D (mm) | Length of clear span (mm) | L/2D | Main reinf. | Concrete: Age at destructive test (days) | Concrete: Compressive strength (MPa) | Concrete: Splitting tensile strength (MPa) |
|---|---|---|---|---|---|---|---|---|---|
| Test A | N series | N-250-A | 255×255 | 250 | 0.50 | 4-φ13 | [illegible] | [illegible] | 3.0 |
| | | N-375-A | | 375 | 0.75 | | 33 | 32 | [illegible] |
| | | N-500(1)-A | | 500 | 1.00 | | [illegible] | 33 | [illegible] |
| | | N-500(2)-A | | | | | [illegible] | 32 | [illegible] |
| | | N-625-A | | 625 | 1.25 | | [illegible] | 32 | [illegible] |
| | | N-750-A | | 750 | 1.50 | | [illegible] | 33 | [illegible] |
| | | N-875-A | | 875 | 1.75 | | [illegible] | 32 | [illegible] |
| | H series | H-250-A | | 250 | 0.50 | | [illegible] | [illegible] | [illegible] |
| | | H-375-A | | 375 | 0.75 | | 33 | [illegible] | [illegible] |
| | | H-500(1)-A | | 500 | 1.00 | | 33 | [illegible] | [illegible] |
| | | H-500(2)-A | | | | | [illegible] | [illegible] | [illegible] |
| | | H-625-A | | 625 | 1.25 | | [illegible] | [illegible] | [illegible] |
| | | H-750-A | | 750 | 1.50 | | [illegible] | [illegible] | [illegible] |
| | | H-875-A | | 875 | 1.75 | | [illegible] | [illegible] | [illegible] |
| Test C | N series | N-250-C | 125×250 | 250 | 0.50 | 4-φ9.2 | [illegible] | [illegible] | [illegible] |
| | | N-375-C | | 375 | 0.75 | | [illegible] | 32 | [illegible] |
| | | N-500-C | | 500 | 1.00 | | 35 | 32 | [illegible] |
| | | N-625-C | | 625 | 1.25 | | [illegible] | 31 | [illegible] |
| | | N-750-C | | 750 | 1.50 | | [illegible] | 33 | [illegible] |
| | | N-875-C | | 875 | 1.75 | | [illegible] | 31 | [illegible] |
| | H series | H-250-C | | 250 | 0.50 | | [illegible] | [illegible] | [illegible] |
| | | H-375-C | | 375 | 0.75 | | [illegible] | [illegible] | [illegible] |
| | | H-500-C | | 500 | 1.00 | | [illegible] | [illegible] | [illegible] |
| | | H-625-C | | 625 | 1.25 | | [illegible] | [illegible] | [illegible] |
| | | H-750-C | | 750 | 1.50 | | 32 | [illegible] | [illegible] |
| | | H-875-C | | 875 | 1.75 | | 3 | [illegible] | [illegible] |

Test A: [illegible]    Concrete: [illegible]
Test C: Compression-bending shear test under constant axial load.    L/2D: Shear span / Depth ratio

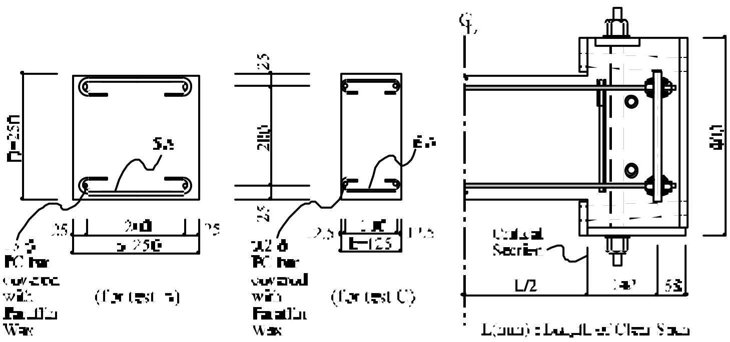



**Figure 9: Examples of specimens**

**Table 4: Mechanical properties of main reinforcements**

| PC bar | 13φ | 9.2φ |
|---|---|---|
| Nominal diameter (mm) | 13 | 9.2 |
| Actual diameter (mm) | 12.87 | 9.27 |
| Yield strength (N/mm²) | 1232 | 1232 |
| Young's modulus (kN/mm²) | 200 | 200 |
| Classification of test piece (JIS Z2201) | No.2 | No.2 |

strength and high-strength concrete were grouped into N series and H series, respectively. Six different shear span ratios, 0.50, 0.75, 1.00, 1.25, 1.50, and 1.75 were employed. The dimension of the section for columns on test A and test C is different, as shown in Figure 9. This difference is due to different capacity of laboratory apparatus used in this investigation. PC bars for main reinforcements were covered with paraffin wax and cellophane tape to remove the bond [6]. The mechanical properties of the main reinforcements are shown in Table 4.

**Test Results:**

Figure 10 shows representative test results, where vertical axis expresses shear load of concrete and horizontal axis expresses end rotation. The load of concrete is calculated by subtracting the load of main reinforcement from the load of R/C column. Twenty-four out of twenty-six specimens failed in shear, whereas two, N-875-A and H-875-C, failed in flexure. Depend on the appearance of shear crack observed during testing, all specimens are divided into three groups, as shown in Figure 10. The group (a) consists of the specimens which shear stress increases after appearance of shear crack.

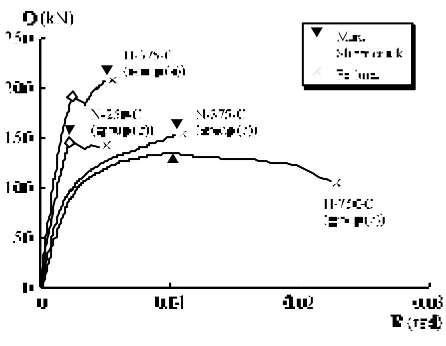



**Figure 10: The test results (load-end rotation curves)**

The group (b) consists of the specimens which shear stress decreases after appearance of shear crack. The group (c) consists of the specimens which shear crack doesn't appear until failure.

**Estimation of Shear Cracking Stress:**

Consider first the estimation of shear cracking stress. The test results of the specimens that belong to the group (a) and (b), which shear cracks appear before failure, are estimated here. The column is assumed to act as an arch [5], as shown in Figure 11. A section of the arch, which meets at right angle to an axis of the column, is considered to calculate biaxial principal stresses. Biaxial shear cracking criterion that is condition of first shear crack appearance can be assumed. Darwin-Pecknold criterion is used here as shown in Figure 12 [3]. From these assumptions the shear cracking stresses were calculated, and the results were plotted as dot-line, as shown in Figure 13. In Figure 13, the test results were also plotted as four kind of marks. Vertical axis expresses ratio of average shear stress ( $\tau_C$ ) and concrete compressive strength ($\sigma_B$). Average shear stress is equal to shear load of concrete divided by section aria. Horizontal axis expresses shear span ratio. A star mark (*) stands for the specimen that belong to the group (b), which shear stress decreases after appearance of shear crack. Concrete tensile strength ( $\sigma_T$ ) is equal to $1.7\sqrt{\sigma_B}$ , and the results agree with tensile strength by splitting cylinder test. It was found through Figure 13 that the test results are almost constant regardless of shear span ratio when concrete strength is same, and it can be said that the curve of calculation express that. It can be seen from this figure that the curve for H series shows good agreement with the test results, but for N series results under estimate. A proper biaxial shear cracking criterion will be able to suggest by collecting more test data, experimentally.

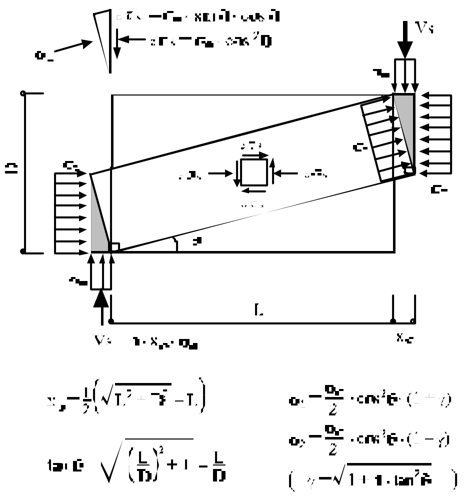


**Figure 11: Arch model for shear crack**

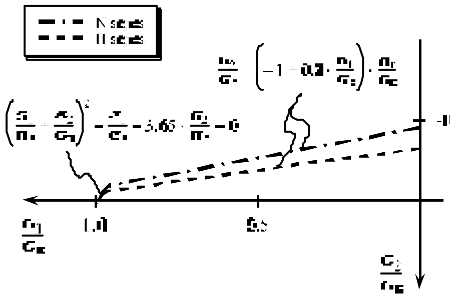


**Figure 12: Darwin-Pecknold criterion**

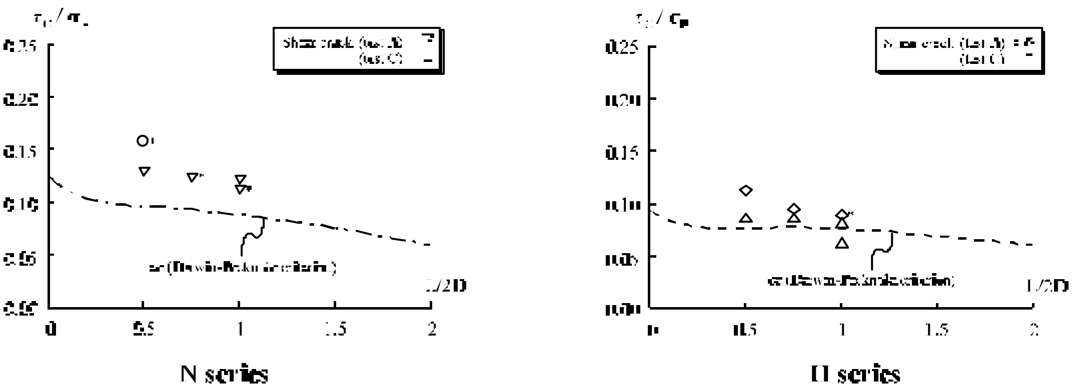



**Figure 13: The test results and calculation of shear cracking stress**

**Estimation of Shear Strength:**

Maximum stress of all specimens is estimated by assuming an arch in the column as shown in Figure 14 [5]. The test results of shear strength (maximum stress) were plotted as four kind of marks in Figure 15. It was found that maximum stress tends to decrease as shear span ratio increases, but there is no rule to decide shear strength exactly. For this reason an upper bound and a lower bound of shear strength is proposed in this paper. The upper bound of shear strength is equal to arch strength, and the lower bound of shear strength is taken as 65% of arch strength. The arch strength is decided when uniaxial compressive stress ($\sigma_O$) in the arch is equal to the concrete compressive strength ($\sigma_B$). The upper bound and the lower bound agree with the test results of shear strength, as shown in Figure 15.

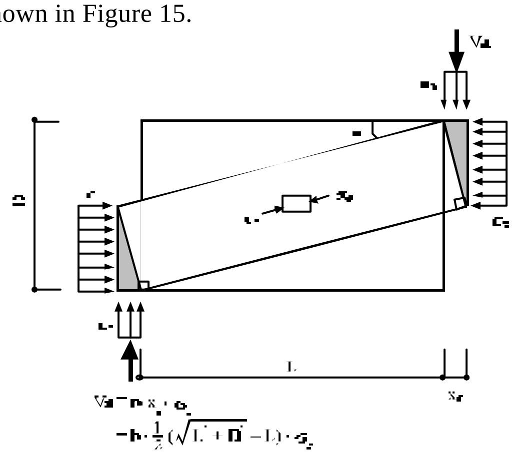


**Figure 14: Arch model for shear strength**

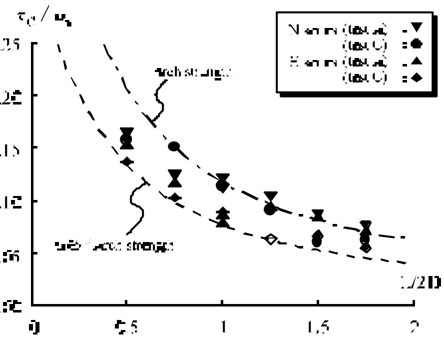


**Figure 15: The test results and calculation of shear strength**

## CONCLUSIONS

Compressive properties of concrete around the critical section and shear stress transfer mechanism of concrete of R/C columns were studied to estimate flexural strength, shear cracking stress, and shear strength under combined compression, bending and shear. Based on the experimental results presented in this paper, the following conclusion and design recommendation are drawn:

1. On the assumption of the equivalent rectangular distribution of compressive stress of concrete of R/C columns, the maximum stress value factor kmax of the test results of specimen subject to combined compression, bending, and shear is approximately 1.35 times larger than that subject to combined compression and bending, which is used for ACI Building Code. Other than loading combinations, that is combined compression, bending and shear, and combined compression and bending, parameters investigated in this paper had little influence on the stress value of stress block.
2. In shear design, compressive properties of concrete for the calculation of flexural strength of R/C columns should be evaluated based on the normalized Mc-Nc interaction proposed in this paper. In addition, more attention should be paid to the difference of compressive the properties when the axial force ratio of the column is around 0.4.
3. Shear cracking stress of R/C columns without shear reinforcements can be estimated by assuming an arch model in the column and biaxial shear cracking criterion on the section that meets at right angle to an axis of the column.
4. The upper bound of shear strength of R/C columns without shear reinforcements is equal to the arch strength, and the lower bound of shear strength is taken as 65% of the arch strength.

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