SHEAR RESISTANCE OF DEEP REINFORCED CONCRETE CORBELS IN CONTINUOUSLY BUCKLING RESTRAINED BRACED RC FRAMES

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Abstract

In this study, it is examined that shear resistance of deep RC corbel adopted to apply buckling restrained brace for RC frames. RC corbels has very small aspect ratio and uniformly distributed stirrups. The experimental and analytical study on the shear resistance of such BRB connections is reported in this paper. Two series of shear test of the reinforced concrete corbels were carried out. As a result of the test, shear strength of corbel and strain distribution in stirrups were provided. The strain distribution of stirrups was confirmed to be linear distributed with yield strain at the loading edge and zero strain at the far end. Finite element analysis that reproduced the component test was carried out. As a result of the analysis, shear strength and stiffness showed good correspondence to the test results. The strain distribution of stirrups confirmed the same tendency as that in the component test. A strut-and-tie model is proposed to estimate the shear strength of the corbels. It gives satisfying estimate for all the specimens in the current test program, except the one with insufficient anchor of the stirrups.

Keywords: Deep Corbel, Finite Element Analysis, Shear Resistance, Strut-and-Tie Model

1 Introduction

In recent years, applications of buckling restrained braces (BRBs) in reinforced concrete (RC) frames have attracted much attention, in which, the connection of BRBs to RC frames is important. However, there are not commonly accepted details of installing BRBs on RC frames. The authors suggested a continuously buckling restrained braced frame (CBRBF) system in which the BRBs are arranged in the form of a Warren truss (Maida et al, 2012; Qu et al, 2012). This system was mainly intended for tall buildings. The BRBs in the adjacent stories share the same gusset plate, which is fastened to the concrete beam-to-column joint by prestressing bolts and is kept by a pair of RC corbels that project from the column surface. In such a manner, the prestressing bolts are mainly responsible to resist the horizontal force while the RC corbels the vertical one (Figure 1).

In this study, RC corbels has very small aspect ratio and uniformly distributed stirrups. The corresponding BRB connection details in the proposed system have been confirmed effective through RC subassemblage tests with BRBs. However, behavior of the corbel is complicated and the subassemblage tests did not lead to the grasp of the shear strength of corbels. In the case of tall buildings, it is necessary to grasp of the shear strength of corbels because BRBs of large strength is used. In this paper, the shear strength of RC corbels and force transmission in stirrups and concrete are investigated by component test and finite-element analysis. A strut-and-tie model is also proposed based on the results of the test and analysis.

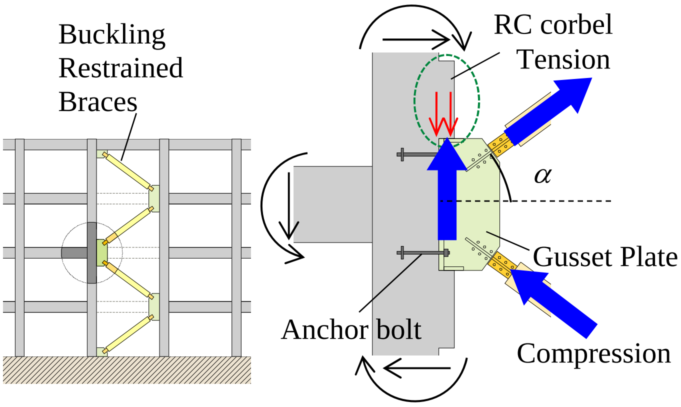


Figure 1 Continuously braced frame with buckling restrained braces

2 COMPONENT TEST OF CORBELS

2.1 Outline of test

First, component tests were performed on two series of deep RC corbels. Two series of test, namely Series C and Series S, of RC corbel specimens with different details, were carried out.

2.1.1 Specimens

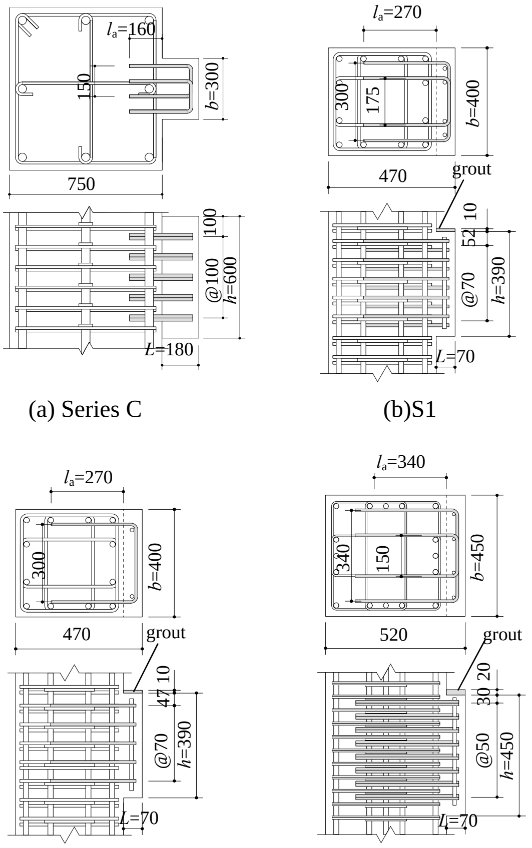
Specimens in either Series C or Series S have identical dimensions, as depicted in Figure 2. Series C specimens have an aspect ratio L/H of 0.3, which leads to a nominal shear span-to-depth ratio as small as 0.15, assuming uniform pressure on the corbel edge. This ratio for Series S is even smaller, about 0.09. Major properties, including the concrete compressive strength, σ_B, stirrup yield strength σ_y, stirrup nominal diameter, d_s, total number of stirrup legs, n_{leg}, the ratio of anchorage length to nominal diameter of bar, l_a/d_s, the dimensions of the corbels, and loading history, of the specimens in Series C and S are listed in Table 1. C1 is regarded as a control specimen in Series C. The other four specimens are design to show the influence of the concrete strength (C2), amount of stirrups (C3) and anchorage of stirrups (C4) on the behavior of the corbel.

Specimens in Series S were actually taken from the tested specimens of subassemblies, each of which consists of a RC beam framing into a RC column with connections for buckling restrained braces (Maida et al, 2012; Qu et al, 2012). Some minor cracks were observed on the corbels during the subassembly test. However, the influence of this slight damage to those corbels on their ultimate strength was considered negligible. The only difference between S1 and S2 is the amount of stirrups in the corbels. In addition, the only difference between S3 and S4 is the loading histories.

2.2 Loading setup and measurement

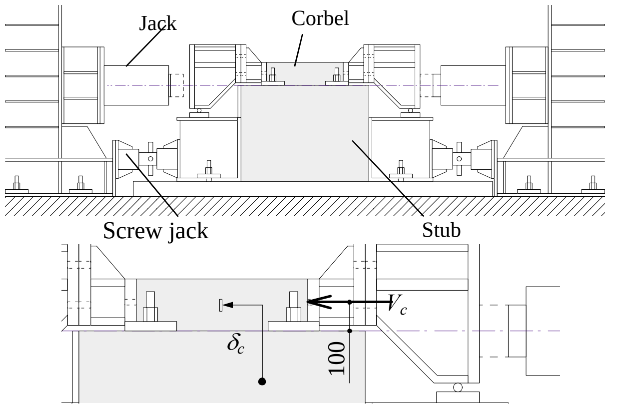
Series C specimens were subjected to cyclic loading by means of two actuators on both sides of the corbel, pushing it by turns, as demonstrated in Figure 3(a).For Series S, a self-balanced loading system, as depicted in Figure 3(b), was adopted. The loading jig was connected to 4 high-strength steel rods, the other ends of which were connected with an H steel beam. An actuator was installed between the H steel beam, which was resting on a roller cushion, and the end of the RC subassembly, which was fixed to the ground, pushing the two apart from each other and thus pulling the loading jig to impose shear force on the corbel.

The shear deformation of each corbel in Series C was recorded through six displacement transducers installed between half span of the corbel and the top surface of the underneath concrete monolith. The average of the displacement of the two transducers closest to the loading edge was taken as the shear deformation of the corbel under that load. Two displacement transducers were used to measure the slip of each corbel in Series S.For both series, the strain of the corbel stirrups was recorded through strain gages located at the shear surfaces, i.e., the bottom of the corbels. A pair of strain gages was adopted for a single leg of stirrups and their average reading is taken as the strain of the stirrup leg.



(a) Series C (b)S1 (c)S2 (d)S3, S4

Figure 2 Details of specimens



(a) Series C (b) Series S

Figure 3 Loading setup of corbel shear test

Table 1 Properties of specimens

ID	Dimension of corbel L (mm)	h (mm)	b (mm)	d_s (mm)	n_{leg}	l_a/d_s	Loading	Material property of concrete σ_B (N/mm^2)	σ_T (N/mm^2)	E_c (N/mm^2)	Material property of stirrup σ_y (N/mm^2)	σ_u (N/mm^2)	E_s (N/mm^2)
C1	180	600	300	16	4×5	10	Two-way cyclic	44.0	-	-	347	514	2.01×10^5
C2								40.1					
C3				13	4×5			44.0			379	532	1.95×10^5
C4				16	4×5	5					347	514	2.01×10^5
S1	70	390	400	10	4×5	27	Monotonic	58.2	3.50	3.30×10^4	346	482	1.79×10^5
S2					2×5								
S3	70	450	450		4×8	34		65.8	3.56	3.31×10^4	366	520	2.03×10^5
S4							One-way cyclic						

(L: length, h: height, b: breadth, d_s: diameter of stirrup, n_{leg}: total number of stirrup legs, l_a/d_s: ratio of anchorage length to nominal diameter of stirrup, σ_B: compressive strength, σ_T: tension strength, E_c: Young's modulus of concrete, σ_y: yield strength, σ_u: ultimate strength, E_s : Young's modulus of steel)

2.3 Discussion on the test results

2.3.1 Relationship of shear force versus displacement of corbel

The relationship of shear force versus displacement of Series C specimens are depicted in Figure 4. The relationships of all the other specimens are compared with that of C1 in these graphs to show the influence of various parameters. For C2 and C3, it is observed that, as expected, the shear strength of the corbels decreases with the reduction in the concrete strength or the amount of stirrups (Figure 4(b) and (c)). Specimen C4 seems to have experienced premature failure due to insufficient anchorage of the corbel stirrups. Its shear strength is only about 43% of that of C1 (Figure 4(d)).

Next, the relationships of shear force versus displacement of corbels in Series S are depicted in Figure 5. For all the specimens, the load increases almost linearly with the displacement up to a very high level of shear force. It is then followed by a sudden brittle failure, which is accompanied by the breaking up of the concrete cover. The corbels with half amount of stirrups (S2) exhibit only about 25% decrease in shear strength as compared with S1. S3 specimen increased the amount of stirrups and dimensions of corbels than S1, but the maximum strength was reduced by about 15%. In this case it seems that shear span increased, because jigs rose. The maximum strength in the one-way cyclic test (S4) is on a par with that in specimen S3.

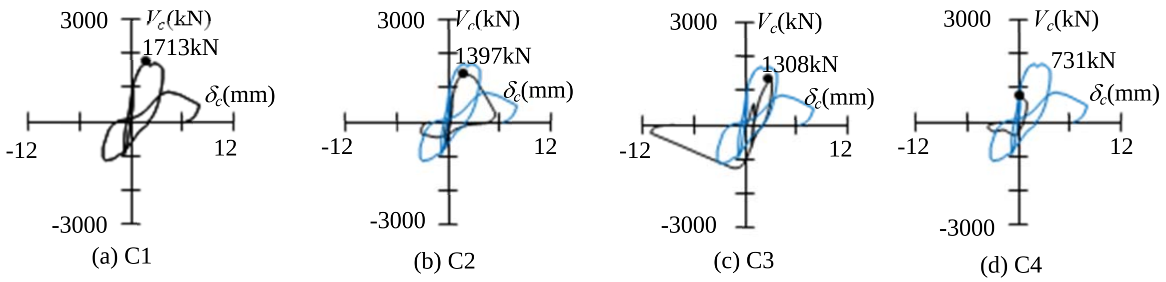


Figure 4 Load-displacement curve (Series C)

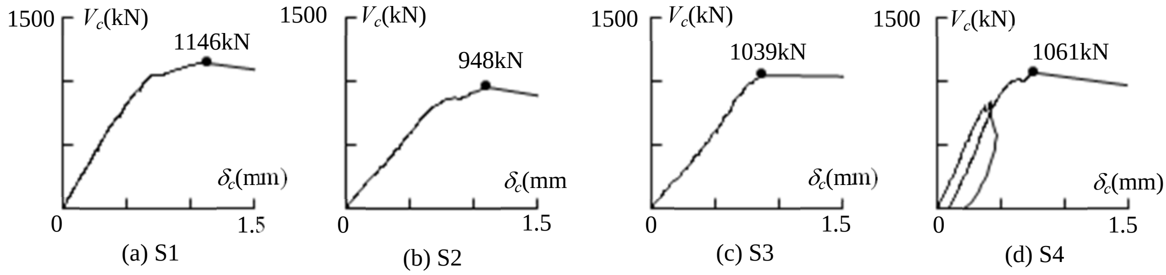


Figure 5 Load-displacement curve (Series S)

2.3.2 Strain distribution in stirrups

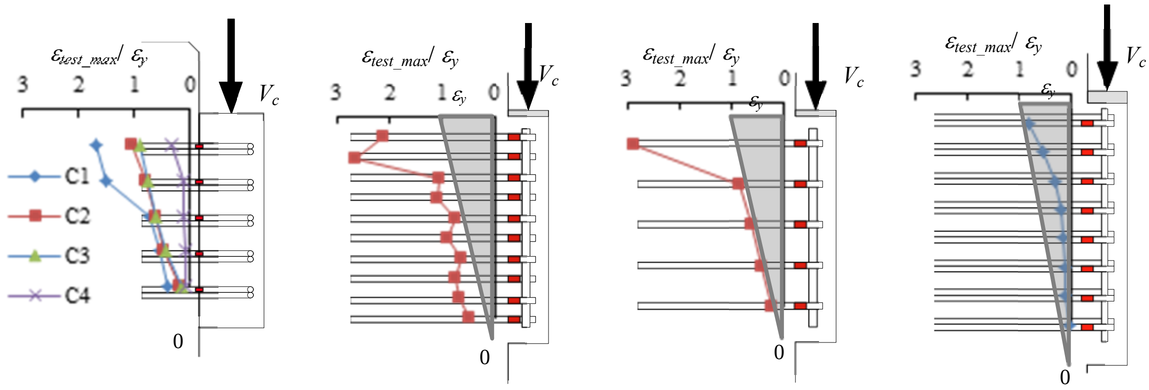
The strain in the stirrups at the maximum shear force is retrieved from the test database and is denoted as ε_{max}. It is then normalized by the yield strain ε_y of the stirrups and is depicted in Figure 6. The horizontal axis is the distance to loading edge normalized by the height, *H*, of the corbel. It is observed that ε_{max} generally reduces linearly with the distance of the stirrup to the loading edge. Several obvious exceptions should be noted.

1) The strain in the stirrups of SpecimenC4 seems to have very insufficiently developed, even in those closest to the loading edge. It is likely that the stirrups experienced premature anchorage failure due to the insufficient development length.

2) For Series S, the strain in the stirrups closest to the loading edge seems to have increased wildly and is much greater than that in the following stirrups.

3) The ε_{max} to ε_y ratios of S1 exhibit a zigzag distribution along the distance. This is considered the consequence of un-uniformly distributed deformation along the width of the corbel. It was observed, after the crushed concrete cover was removed, that the top horizontal portions of the

stirrups, especially those close to the loading edge, were obviously bent with greater deformation in the middle and smaller one at both ends.



(a) Series C (b) S1 (c) S2 (d) S3

Figure 6 Distribution of strain in stirrups

3 FINITE ELEMENT ANALYSIS OF CORBEL

Next, three dimensional finite element analysis that reproduced the component test was carried out. The analysis was intended for only S series specimens.

3.1 Outline of analysis

3.1.1 Modeling

‘‘FINAL Ver.11” (ITOCHU Techno-Solutions Corporation) is used for analysis. The half of the specimen is modeled using the symmetric condition on the shape and loading as three dimensional finite element analysis. The finite element model and boundary condition are shown in Figure 7.
The concrete and end plate are modeled by hexahedral elements. The rebar is modeled by beam element. Joint-type elements are inserted between hexahedral elements and beam elements for the purpose of incorporating bond slip behavior.

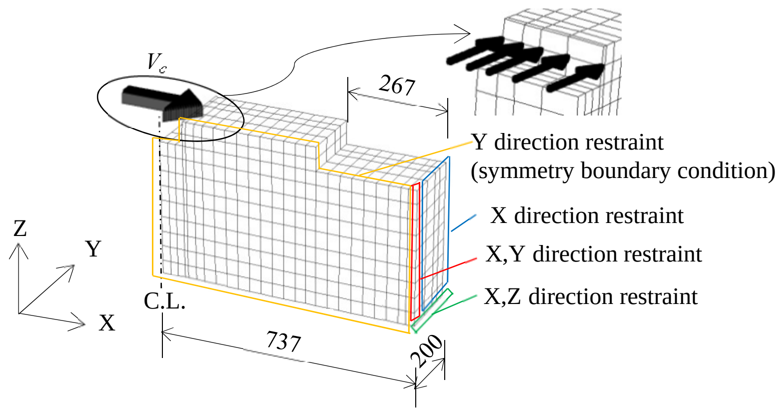


Figure 7 Finite element models

3.1.2 Material property

(a)Concrete
The concrete model is shown in Figure 8. In tensile side, the linear model was applied for the concrete model before cracking. After cracking, the tension softening was considered by Izumo’s model (Izumo et al., 1987). In compressive side, the modified Ahmad’s model (Naganuma, 1995) was applied for the concrete model before maximum stress. After maximum stress, the Nakamura & Higai’s model (Nakamura & Higai, 1999) was applied for one. Three-dimensional analysis employs Kosaka’s four parameter model (Kosaka et al., 1985) for the failure criterion under a

triaxial stress state. The Al-Mahaidi model is applied for shear transmission characteristic of the cracking plane. The compressive deterioration characteristic after cracking is considered by Naganuma's proposed equation (Naganuma, 1991).

(b) Steel material

Elasto-plasticity theory based on material test result is applied for steel material (longitudinal rebar, stirrup, steel plate, et al.).

(c)Bond between concrete and rebar

Perfect bond theory is applied for between concrete and longitudinal rebar. On the other hand, Elmorsi model (Elmorsi et al, 2000) is applied for between concrete and stirrup. The bond strength is determined on Design Guidelines of AIJ (AIJ, 1999) of the stirrup in the joint region. Bond slip corresponding to the bond strength is assumed as 0.1 mm.

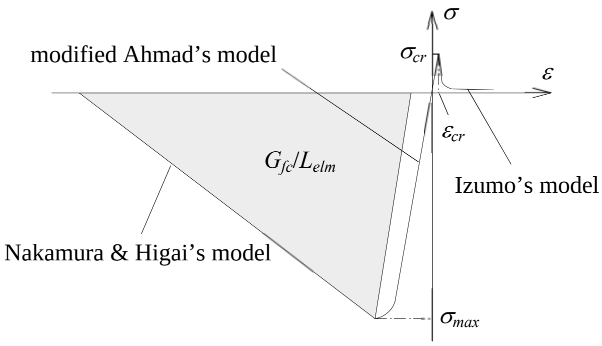


Figure 8 Principal stress- equivalent uniaxial strain relations in concrete

3.2 Discussion on the analysis results

3.2.1 Relationship of shear force versus displacement of corbel

Comparison of the analytical and experimental shear force versus displacement is depicted in Figure 9.For S1 and S2 specimen, shear strength and stiffness showed good correspondence to the test results. Analysis results are larger than test results about stiffness of S3 specimen. For S4 specimen, shear strength of analysis results are smaller than test results. It is thought that influence of one-way cyclic loading appeared larger than an experiment.

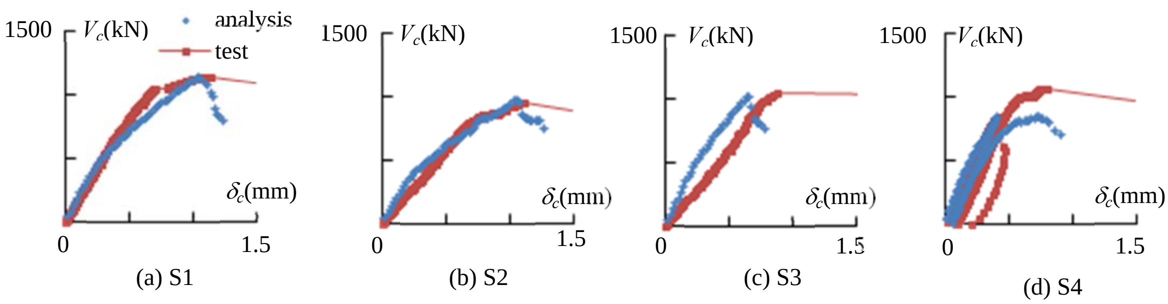


Figure 9 Load-displacement curve (analysis result)

3.2.2 Strain distribution in stirrups

Comparison of the analytical and experimental strain distribution in the stirrups at the maximum shear force is depicted in Figure 10. For all specimens, the analytical strain distribution of stirrups confirmed the same tendency as that in the test. The specimen with much number of the stirrup reached maximum shear force in small strain the stirrup by the analysis. On the other hand, as for the principal stress of the concrete, the specimen with much number of the stirrup is larger. Therefore, it is thought that the concrete damaged before stirrup showed resistance.

3.2.3 Principal stress distribution of concrete

Analytical result of principal stress distribution of the concrete is depicted in Figure 11. The compression principal stress of the concrete near to the loading point acts parallel to loading direction. On the other hand, the compression principal stress of the concrete remote from loading point acts toward the column.

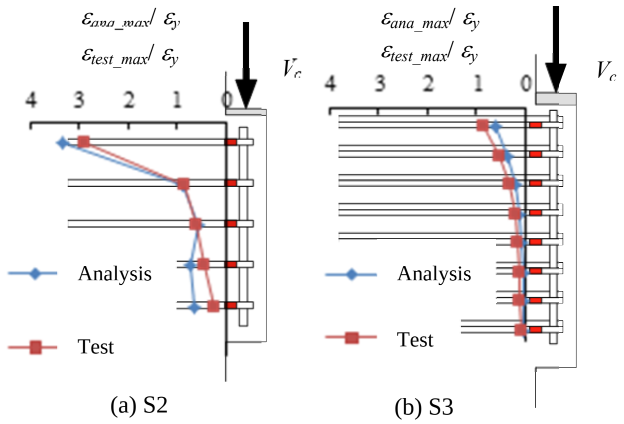


Figure 10 Distribution of strain in stirrups (analysis result)

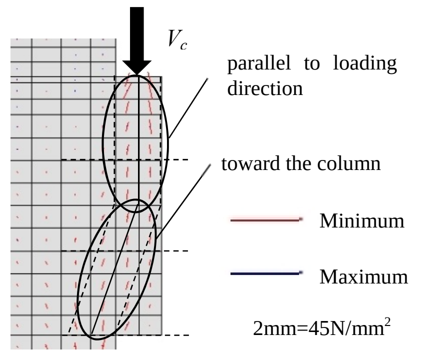


Figure 11 Distribution of principal stress in concrete (analysis result)

4 STRUT-AND-TIE MODEL

Finally, a strut-and-tie model is proposed to estimate the shear strength of deep corbels.

4.1 Modified version of the strut-and-tie model

A strut-and-tie model, as shown in Figure 12, is adopted to predict the shear strength of the corbels. It is a modified version of the strut-and-tie model used by Russo et al (2005) in their derivation. The following two major modifications are made.

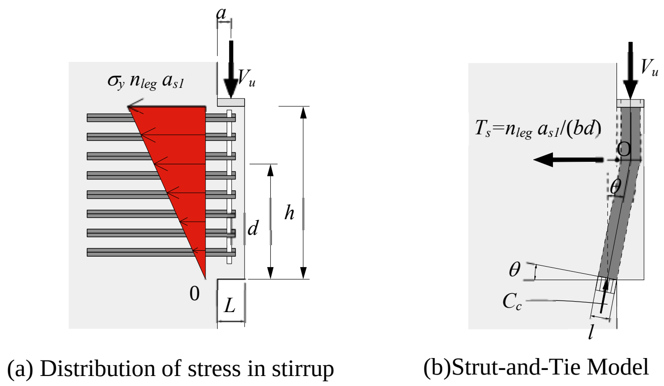


Figure 12 Shear resistance mechanism of corbel

1) By assuming that the shear contribution of the strut-and-tie system, which is formed by a concrete strut and the primary stirrups close to the loading plate, and that of the secondary stirrups are independent, Russo et al (2005) proposed a two-term formula to predict the shear strength of the corbel. The first term is for the strut-and-tie system and the second for the secondary stirrups. However, instead of evaluating the dowel action of the secondary stirrups, they again assumed a strut-and-tie system consisting of the secondary stirrups when evaluating the second term. In such a manner, they may have double counted the strength of the concrete strut. In this paper, the second term of the formula by Russo et al (2005) is removed and the imperial factor of 0.8 on the first term by data fitting is correspondingly abandoned. Thus, Eq. 1 is used herein to evaluate the shear strength, V_u, of RC corbels.

$$V_u = \sigma_d b l \cos\theta \tag{1}$$

where σ_d is the softened compressive strength of the diagonal concrete strut; b is the width of the corbel; l and θ is the depth and inclination angle of the concrete strut, respectively. All these variables can be explicitly evaluated by Eq. 2-4 proposed by Russo et al (2005).

$$\sigma_d = \begin{cases} \dfrac{0.9\sigma_B}{\sqrt{1+400\frac{\sigma_T}{E_c}}} & \text{for } \sigma_B < 42\ [\mathrm{N/mm^2}] \\ \dfrac{5.8\sqrt{\sigma_B}}{\sqrt{1+400\frac{\sigma_T}{E_c}}} & \text{for } \sigma_B \geq 42\ [\mathrm{N/mm^2}] \end{cases} \tag{2}$$

$$l = kd = \left(\sqrt{(n\rho_s)^2 + 2n\rho_s} - n\rho_s\right)\cdot d \tag{3}$$

$$\theta = 2\arctan\left(\frac{-1+\sqrt{\left(\frac{a}{d}\right)^2+\left(1-\frac{k^2}{4}\right)}}{\frac{a}{d}-\frac{k}{2}}\right) \tag{4}$$

where n=E_s/E_c, is the ratio of steel and concrete Young's modulus; σ_T is the tensile strength of concrete; d is the effective depth of the corbel and ρ_s is the primary stirrups ratio of the corbel.

2) Because the stirrups are uniformly distributed along the depth of the corbels, no primary stirrups can be readily extinguished from others. As a result, effective d and ρ_s are proposed herein. A linear distribution of stirrup stress is assumed. The stirrup stress on the loading edge is assumed to be the yield strength, σ_y, while that on the other end is 0 (Figure 12). Compared with the measured strain of the stirrups at failure in Figure 6 & 10, the assumed stress distribution is reasonable and conservative. With the assumed stirrup stress distribution, the effective depth of the tie and the effective stirrup ratio can then be calculated by Eq. 5 and 6.

$$d = (2/3)h \tag{5}$$

$$\rho_s = 0.5n_{leg}A_{s1}/(bd) \tag{6}$$

where A_{s1} is the cross-section area of a single stirrup leg.

The shear strengths calculated by Eq. 1-4, denoted as V_{u_cal}, and those obtained in the test are compared in Figure 13. The calculated results generally agree well with the experiment and fall into a 20% error band. An exception is specimen C4, whose stirrups sustained premature bond-slip failure due to insufficient anchorage.

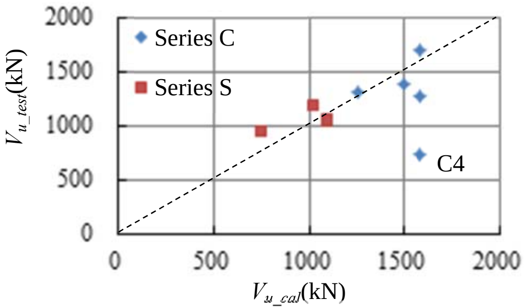


Figure 13 Calculated and test shear strength

5 CONCLUSIONS

In this study, the shear strength of RC corbels and force transmission in stirrups and concrete are investigated by component test and finite-element analysis. In addition, a strut-and-tie model is also modified based on the results of the test and analysis. The result that was provided summarize below.

1) Component tests of deep RC corbels specimens with different details (concrete compressive strength, stirrup yield strength, stirrup nominal diameter, total number of stirrup legs, the ratio of anchorage length to nominal diameter of bar, the dimensions of the corbels, and loading history)

were carried out. As a result, shear strength of corbel and strain distribution in stirrups were provided. The strain distribution of stirrups was confirmed to be linear distributed with yield strain at the loading edge and zero strain at the far end.

2) Three dimensional finite element analysis that reproduced the component test was carried out. As a result of the analysis, shear strength and stiffness showed good correspondence to the test results. The strain distribution of stirrups confirmed the same tendency as that in the component test. Furthermore, the principal stress distribution of the concrete was shown.

3) A strut-and-tie model is proposed to estimate the shear strength of deep corbels. It gives satisfying estimate for all specimens in the current test program, except the one with insufficient anchor of the stirrups.

Acknowledgement

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