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Experimental study on high-strength R/C member in tension and shear

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ABSTRACT: The relations between the axial tensile force and the shear strength of the high-strength R/C member are discussed from experimental data. In the experiment, 16 specimens were provided that have various compressive strengths of concrete and have two types of tensile strengths of rebar. Test results showed that the members subjected to axial tension had decreased load-carrying capacity. Furthermore, it became clear that in the case of a higher strength concrete beam subjected to axial tension, the shear strength of the beam declined rapidly. On the other hand, it was confirmed that the axial tensile force shifts the destruction mode from shearing to bending. In this case, the axial tensile force contributes to a reduction of the compressive stress in the concrete compression region, when the ultimate loading capacity of the member increased finally.

1 INTRODUCTION

Recently in cities, many superstructures are built on large and tall scales. High-strength concrete has been used as a primary building material, because has about 3–5 times the compressive strength and higher durability in comparison with normal concrete. These characteristics are used to make many skyscrapers and to reduce the cross-section of the members and so on. The effective use of the land and the expansion of the residential space due to the span expansion became possible as a result.

The fracture property of a reinforced concrete member has been studied by many researchers. From those results, although the shear fracture is complicated, the fracture mechanism was clarified and the design equation was sufficiently accurate. However, in the case of the member subject to the axial force and shear, there are only a few studies. In a previous paper, the author reported on a reinforced concrete beam that underwent axial force and bending. In the case of high-strength concrete, the investigation of a similar situation is very important. This research aims to clarify the fracture mechanism of a high-strength concrete member subjected to axial force and shear.

2 ULTIMATE STRENGTH

2.1 *Ultimate bending strength*

The ultimate bending strength of the member considering the axial force is calculated by the following Equation 1. The influence (i.e., stress intensity) by axial tension is taken into consideration by conversion into the bending stress intensity.

$$M_u = (A_s \cdot f_{yd} - A'_s \cdot \sigma'_s) \cdot [d - (a/2)] + A'_s \cdot \sigma'_s \cdot (d - d') \pm N \cdot I/(A \cdot y) \quad (1)$$

where M_u = ultimate moment ($kN \cdot cm$); A_s = area of the tensile rebar, A'_s = area of the compressive rebar; f_{yd} = yield stress of rebar; σ'_s = compressive stress of rebar; d = effective depth; d' = depth of the compressive rebar; a = equivalent depth of concrete compressive area; N = axial force (positive for compression); I = moment of inertia; A = area of concrete; y = distance to the tensile rebar from the center of gravity.

2.2 *Nominal shear strength*

Nominal shear strength of a reinforced concrete (R/C) member is generally determined by concrete strength, reinforcement ratio, effective depth of a cross-section, shear span to depth ratio, and applied axial force. For example, in the JSCE design equation, the shear strength of an R/C beam with shear reinforcement (V_{yd}) is calculated as the following Equation 2. However, in JSCE, an upper limit is set on the term of the concrete design strength if the concrete compressive strength exceeds 0.72 N/mm^2.

$$V_{yd} = V_{cd} + V_{sd} \quad (2)$$

where,

$$V_{cd} = \beta_d \cdot \beta_p \cdot \beta_n \cdot f_{vcd} \cdot b_w \cdot d/\gamma_b \quad (3)$$

$$f_{vcd} = 0.20\sqrt[3]{f'_{cd}} \ \ (\text{N/mm}^2) \quad (4)$$

Here, $f_{vcd} \leq$ (N/mm^2)

$$\beta_d = \sqrt[4]{1/d}\ (d : m)$$

β_d is 1.5 when $\beta_d > 1.5$

$$\beta_p = \sqrt[3]{100p_v}$$

β_p is 1.5 when $\beta_p > 1.5$

$$\beta_n = 1 + M_o/M_d\ (N'_d \geq 0)$$

β_n is 2 when $\beta_n > 2$

$$\beta_n = 1 + 2M_o/M_d (N'_d < 0)$$

β_n is 0 when $\beta_n > 0$.

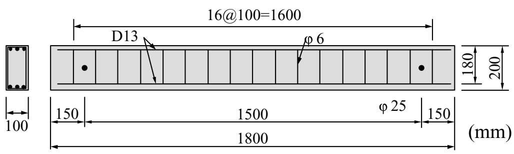

Figure 1. Specimen with stirrup.

Table 1. Material properties of rebar.

Type of rebar	D13(L)	D13(H)	ϕ 6
Yield stress (σ_y: N/mm^2)	334	401	226
Tensile strength (f_t: N/mm^2)	457	643	282
Elastic modulus (E_s: kN/mm^2)	202	208	193

where N'_d is the design axial load, which is taken as positive for compression and negative for tension. M_d is the ultimate moment, and M_o, named the decompression moment, is the bending moment when the axial stress is calculated in bending. If M_o has the same signs to M_d, it is taken as positive. Also, b_w = web width; d = effective depth; $p_v = A_s/(b_w \cdot d)$; A_s = area of tensile rebars; f'_{cd} = concrete design compressive strength; $\gamma_b = 1.3$.

V_{sd} is the shear strength, which is covered by the shear reinforcing bar.

$$V_{sd} = [A_w f_{wyd}(\sin\alpha_s + \cos\alpha_s)/s_s]z/\gamma_b \quad (5)$$

where A_w = total cross-sectional area of shear rebar within the s_s; f_{wyd} = design yield strength of shear rebar, less than 400 N/mm^2; however, in case of the characteristic compressive strength of concrete σ_{ck} over 60 N/mm^2 it is less than 800 N/mm^2; α_s = an angle toward the axis of the center of gravity; s_s = Interval of the arrangement of the shear rebars; z = distance from center of the tensile rebar to center of the compressive stress; $\gamma_b = 1.1$

3 EXPERIMENTAL PROGRAM

3.1 *Specimens*

Figure 1 shows the test beam subjected to axial force. Sixteen specimens were provided. All of the specimens for the experiment have the same dimensions. Three

Table 2. Bending strength.

			Experimental results						M_y/M_u
Specimen	N	f_{ck}^1	P_v	M_v	P_b	M_b	Mode	M_u	(M_b/M_u)
L-A1-0	0	32.9	–	–	69.3	1995	S	2149	(0.93)
L-A1-T40	40	32.9	67.1	1933	69.5	2002	M	1944	1.00
L-B1-0	0	43.5	–	–	73.4	2106	S	2177	(0.97)
L-B1-T40	40	44.4	68.4	1970	80.6	2321	M	1974	1.00
L-C1-0	0	63.7	79.2	2282	107.1	3085	M	2224	1.03
L-C1-T40	40	66.6	67.6	1946	99.2	2856	M	2026	0.96
L-D1-0	0	82.5	82.0	2361	83.7	2411	M	2263	1.04
L-D1-T40	40	84.9	72.0	2073	91.9	2647	M	2063	1.00
H-A2-0	0	27.0	–	–	66.9	1927	S	2550	(0.76)
H-A2-T40	40	27.0	–	–	62.8	1809	S	2345	(0.77)
H-B2-0	0	33.4	–	–	72.1	2078	S	2569	(0.81)
H-B2-T40	40	33.4	74.6	2147	84.8	2442	M	2364	0.91
H-C2-0	0	68.9	87.1	2508	96.0	2765	M	2658	0.94
H-C2-T40	40	68.9	73.8	2125	107	3084	M	2453	0.87
H-D2-0	0	104	–	–	80.6	2321	S	2727	(0.85)
H-D2-T40	40	104	80.0	2303	79.5	2290	S	2522	(0.91)

N: Expected axial force (tension) (kN) f_{ck}^1: Concrete compressive strength (N/mm^2) P_v: Yielding load (kN) M_v: Yielding moment (kNcm) P_b: Breaking load (kN) M_b: Breaking moment (kNcm) M_u: Ultimate bending moment calculated by equation (1) (kNcm) S: Shear failure M: Bending failure.

deformed bars (D13) are placed as the tensile reinforcements and the compressive reinforcement, respectively. Then, there are two types of steel strength: $f_y = 295$ N/mm^2 and 390 N/mm^2. Thirteen stirrups (Φ6) are placed at 15 cm intervals. There is a hole at the both ends of the beam to introduce the axial tension and the points are the supporting points of the all beams. The material properties of both the main and shear rebars are shown in Table 1. Also, Table 2 shows the material properties of concrete. There are four types concrete compressive strengths: approximately 24, 40, 70, and 100 N/mm^2.

3.2 *Test apparatus and procedure*

The testing apparatus for the test with axial tensile force is shown in Figure 2. It is composed of two oil pres-sure actuators controlled by the electro-hydraulic servomechanism. Also both supporting points are hinged by bearing joints. In the test of the member subjected to axial tension, the axial tension is introduced onto both ends of the beam via a longitudinal actuator and is held constant after reaching the expected tension.

Next, the transverse loads are provided by the transverse actuator that introduces the load onto two points by the loading beam. The transverse load increases continuously until the beam fails under the displacement controlled system. To determine the shear strength of the member subjected to axial tension, a non-stressed test carried out. During the loading test, new cracks are marked on the face of the beam at each loading stage. Dial gauges are placed at the loading point and the center of the span to measure the deflection of the beam. Then the bending strain is measured by wire strain gauges at the canter of the tensile reinforcement and the top of the beam.

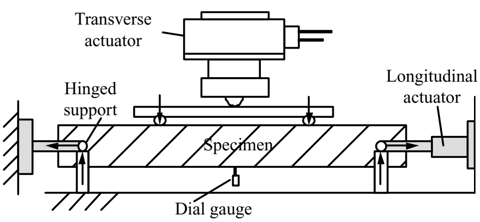

Figure 2. Test apparatus for bending test with axial tension.

4 EXPERIMENTAL RESULTS

4.1 *Ultimate shear strength*

Table 2 shows the experimental conditions, experimental results and the ultimate bending strength, M_u, calculated by the Equation 1. The ultimate state of the fracture mode of the member was divided roughly into bending failure (M) and the shear failure (S) in the Table 2. Table 3 shows the ultimate shear strength, V_b, and nominal shear strength, V_{yd}, calculated in Equation 2 and the terms of the equation. From these tables, it is observed that the beam of type L is in the transition area where a beam fails in bend mode or in shear mode.

In Table 2 and Figure 3, M_y/M_u shows the precision of M_u calculated by Equation 1 against the experimental yield strength M_y. When the member failed in shear,

Table 3. Shear strength.

Specimen	f_{vcd} (N/mm^2)	β_d	β_p	β_n	V_{cd} (kN)	V_{sd} (kN)	V_{yd} (kN)	V_b (kN)	V_b/V_{yd}
L-A1-0	0.60	1.5	1.28	1.00	20.7	13.4	34.1	34.6	1.01
L-A1-T40	0.60	1.5	1.28	0.89	18.7	13.4	32.1	34.8	(1.08)
L-B1-0	0.68	1.5	1.28	1.00	23.5	13.4	36.9	36.6	0.99
L-B1-T40	0.68	1.5	1.28	0.92	21.6	13.4	35.0	39.1	(1.12)
L-C1-0	0.72	1.5	1.28	1.00	24.9	13.4	38.3	53.6	(1.40)
L-C1-T40	0.72	1.5	1.28	0.94	23.4	13.4	36.8	49.6	(1.35)
L-D1-0	0.72	1.5	1.28	1.00	24.9	13.4	38.3	45.9	(1.20)
L-D1-T40	0.72	1.5	1.28	0.95	23.7	13.4	37.1	41.9	(1.13)
H-A2-0	0.60	1.5	1.28	1.00	20.7	13.4	34.1	33.5	0.98
H-A2-T40	0.60	1.5	1.28	0.90	18.7	13.4	32.1	31.4	0.98
H-B2-0	0.68	1.5	1.28	1.00	23.5	13.4	36.9	36.1	0.98
H-B2-T40	0.68	1.5	1.28	0.92	21.6	13.4	35.0	42.4	(1.21)
H-C2-0	0.72	1.5	1.28	1.00	24.9	13.4	38.3	48.0	(1.25)
H-C2-T40	0.72	1.5	1.28	0.94	23.4	13.4	36.8	53.6	(1.46)
H-D2-0	0.72	1.5	1.28	1.00	24.9	13.4	38.3	40.3	1.05
H-D2-T40	0.72	1.5	1.28	0.95	23.7	13.4	37.1	39.8	1.07

f_{vcd}, β_d, β_p, β_n: Term of equation (3) V_{cd}: Shear strength charged by concrete, calculated by equation (3) V_{sd}: Shear strength charged by shear reinforcing bar, V_{yd}: Nominal shear strength calculated by equation (2) V_b: Shear strength (experimental results).

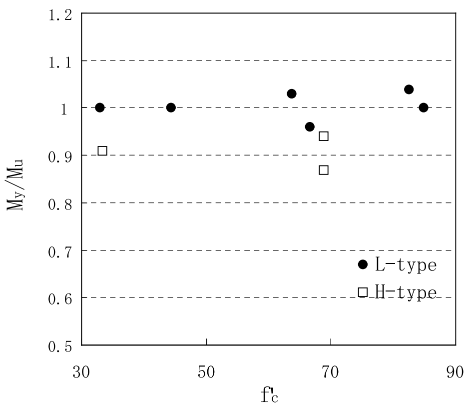

Figure 3. $M_y/M_u f_c'$ relationships (in bending failure).

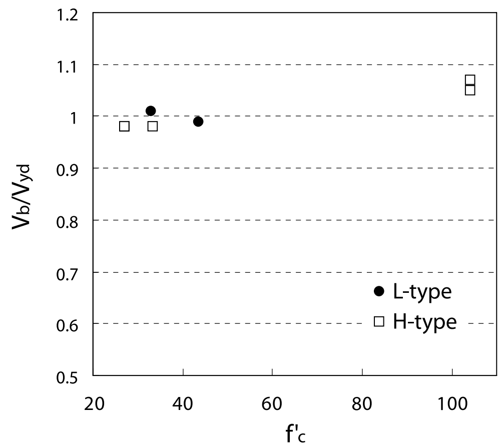

Figure 4. $V_b/V_{yd} f_c'$ relationships (in shear failure).

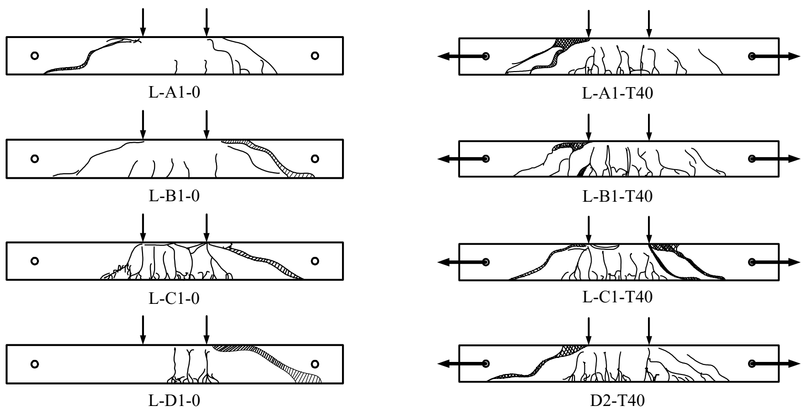

Figure 5. Ultimate crack state (Member subjected to axial tension, SD295).

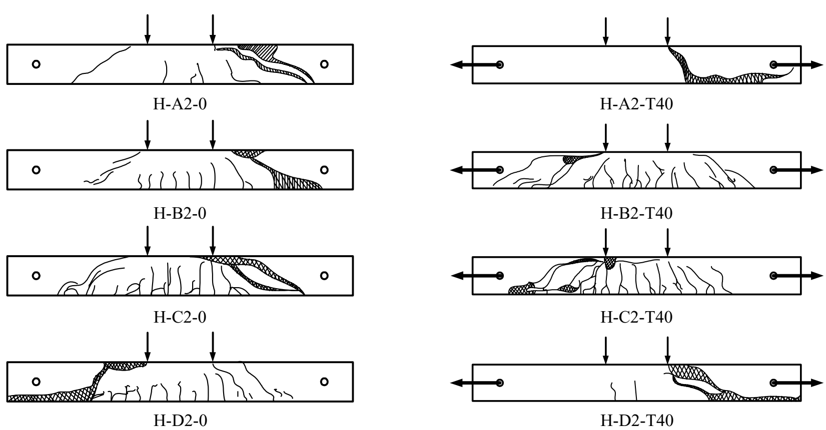

Figure 6. Ultimate crack state (Member subjected to axial tension, SD390).

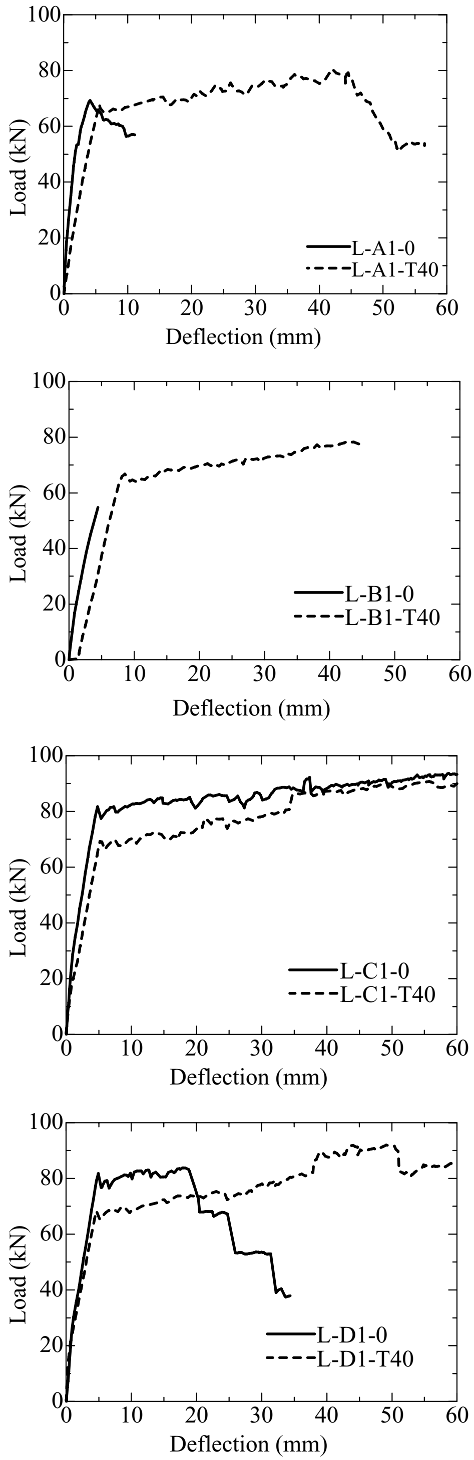

Figure 7. Load deflection relationships (Member subjected to axial tension, SD295).

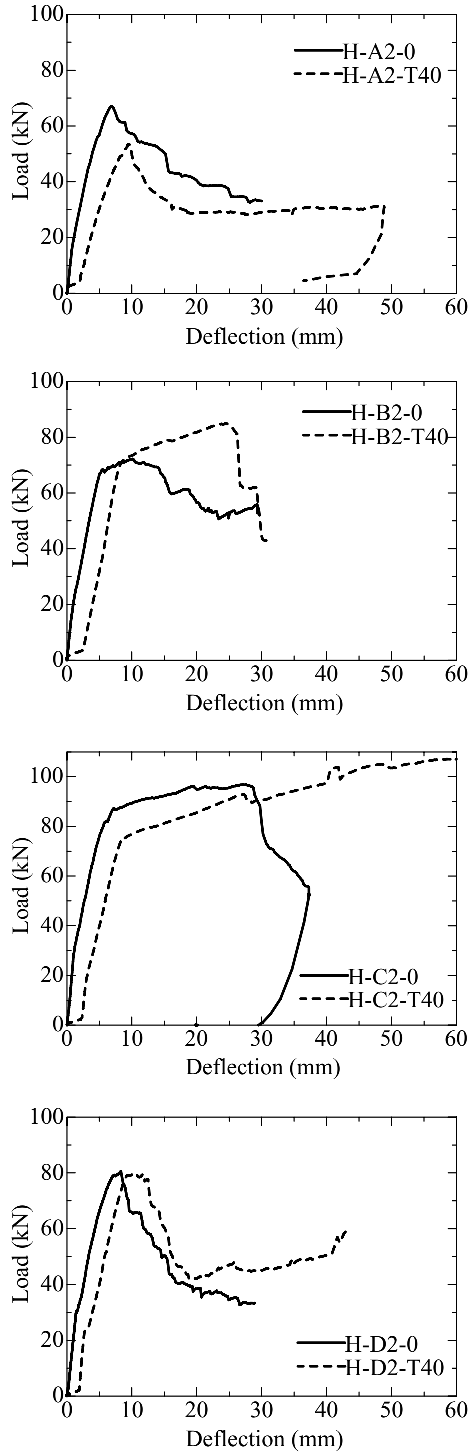

Figure 8. Load deflection relationships (Member subjected to axial tension, SD390).

the M_b/M_u shows the precision of M_u calculated by Equation 1 against the experimental ultimate strength M_b. From this table and these figures, it is clear that Equation 1 is expressing the experimental results with sufficient accuracy in the case of the member that failed at the bending moment. In type L, a normal concrete beam failed in the shear mode. Also, a high-strength concrete beam failed in bend mode. However, all of the type L members failed in shear mode when the members were subjected to axial tension.

In the type H SD390 rebar used, almost all of the beams failed in shear mode. However, (H-B2-T40), (H-B3-0) and (H-C3-T40) failed in bending mode. The accuracy of Equation 1 is declining in these cases.

In Table 3 and Figure 4, V_b/V_{yd} shows the precision of the nominal shear strength V_{yd} calculated by Equation 2 against the experimental shear strength V_b. Here, f_{vcd} of the member with high-strength concrete becomes the upper limit value of 0.72 in accordance with the condition of Equation 3. The safety factor γ_b of concrete material is set to 1.3. From Table 3 and Figure 4, it is observed that, even if the member is subjected to axial tension, Equation 2 expresses the experimental result with sufficient accuracy in the case of the members that failed in shear. However, when high-strength concrete is used, the accuracy of the equation drops compared with the case of the member made of normal concrete.

4.2 *Ultimate crack state*

Figures 5 and 6 show the ultimate crack state of all members. It is observed that the diagonal shear cracks are completed in all members. Also, it is observed that many cracks increased when the beams were subjected to axial tension. In type L beams not subjected to axial tension, cracks spread in wide area as the concrete strength becomes larger. However, in L-D1-0, localized cracks are occurring despite the bending failure. In type L beams subjected to axial tension, cracks spread in a wide area irrespective of the concrete strength. Also, in type H beams not subjected to axial tension, cracks spread in a wide area as the concrete strength became larger. In type H beams subjected to axial tension, cracks spread in a wide area, except for the shear failed beam. Then the beam with the smallest concrete strength and the beam with the biggest strength failed in shear.

4.3 *Load deflection relationships*

Figures 7 and 8 show the load deflection relationship at the center of the beams. These figures show that the value of the load of the bending crack occurrence drops due to the action of axial tension. Then, the value of the load of the occurrence of diagonal shear cracks and the load of the completion of diagonal shear cracks both decrease. The grade of concrete strength influences the stiffness of the member and is related with the inclination of the initial slope of the load deflection relationship. These figures show that the initial inclination of the member is raised by using high-strength concrete. In all of the series, it is confirmed that the displacement at the maximum load of a beam subjected to axial tension is larger than a beam not subjected to axial tension.

5 CONCLUSIONS

To investigate the influence of axial tension on the shear strength of a member using high-strength concrete, an experimental study was conducted. Based on the results, these conclusions can be drawn:

1. Equation 1 expresses the experimental results with sufficient accuracy in the case of members failing at the bending moment.
2. Both Equations 1 and 2 express the bending strength and shear strength with sufficient accuracy for a member using high-strength materials and subjected to axial tension.
3. However, the accuracy of Equation 2 drops in the case of a member using high-strength concrete compared a member using normal concrete.

To clarify the shear strength of a member using high-strength material, a further detailed examination will be required.

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