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Load Transfer Mechanism of a Hybrid Beam-Column Connection System with Structural Tees

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Abstract: The composite frame system with reinforced concrete column and steel beam can be improved in its structural efficiency by complementing the shortcomings of the two systems. The system, however, has many inherent problems in practical design and construction process due to the dissimilarities of the materials. Considering these circumstance, this research aims for the development of a composite structural system which connects the steel beams to the R/C columns with higher structural safety and economy. Basically, the proposed connection system is composed of four split tees, structural angles reinforced by a stiffener, high strength steel rods, connecting plates and shear plates. Structural tests have been carried out to investigate the moment transfer mechanism from the beam flange to steel rods or connecting plates through the structural angle reinforced by a stiffener. The four prototype specimens have been tested until the flange of the beam reached a plastic state. The test results indicated that no distinct material dissimilarities between concrete and steel have been detected for the proposed hybrid beam-column connection system and that the stress transfer through the structural angle between the beam flange and steel rods or connecting plates was very encouraging.

Keywords: composite frame system, moment transfer mechanism, reinforced concrete column-steel beam, connection

1. Introduction

The joint between reinforced concrete column and steel beam should be designed to secure the connectivity of each member and to facilitate the flow of stress on them. Moreover, the structural safety as well as the construction workability and cost must be considered simultaneously. Thus, the development and design of composite structural joint, which is simpler, more efficient, and more convenient for field assembly, is necessary.

This study aims for the development of a new composite structural system for the joint, which connects the steel beams to the R/C columns, by using structural tees and high strength steel rods. Its purpose is to promote the practice of designing such a composite frame system to enhance the structural safety and the economic aspect by delineating the flexural shear force and stress transfer mechanism through structural tests.

2. Experimental plan

2.1 Structural components of test specimen

Fig. 1 is a detailed view of the composite beam-column connection system with structural tees as proposed in this study. The structural tees (T-shaped steel bars) are the most important element among the structural components of the composite beam-column joint to connect all the elements of stress transfer inside and outside the composite system. It maintains the overall shape of the joint and functions with the columnar molding form. In addition, it transfers the tension of the beam flange to the connecting plates and shares the bearing force against shear force of the beam. The system was designed so that the tension of the beam flange could be transferred to steel rods using a structural angle reinforced with a stiffener. Also, shear plates were welded to structural tees to connect with the web of the beam in order to bear the shear force of the beam. The inside of the connection system was made of members transferring the tension of the beam flange. It is composed of high strength steel rod in one direction and steel connecting plates at the perpendicular direction so that the two elements will not interfere with each other. The shear force of the beam was to be beared by structural tees and steel connecting plates. Moreover, structural angles were welded to each top and bottom corner of the structural tees in order to function as a tie bar and to construct the monolithic joint. Table 1 shows the components of the composite joint and the members used in the test specimen.

2.2 Preparation of test specimen

Fig. 2 shows the test specimen by connecting a beam to the composite structural system at the joint. The structural components of the proposed composite connection system transfers the flexural moment of the beam to steel rods in one direction and to connecting plates in its perpendicular direction. Thus, four test specimens were fabricated to investigate the difference in the behavior of these composite elements to transfer

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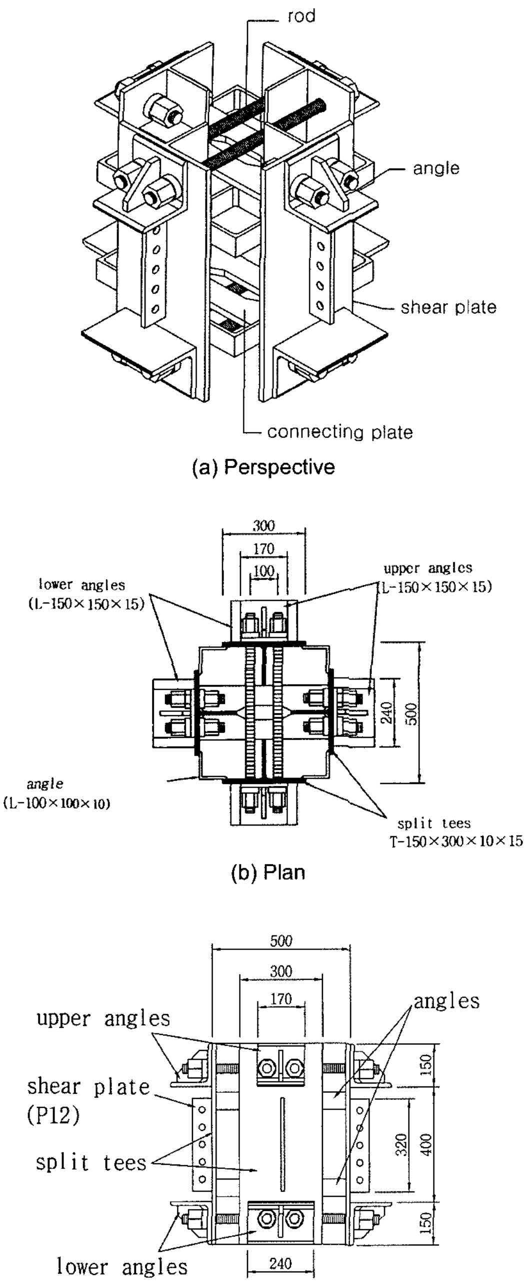


Fig. 1 Composite beam-column connection system with structural tees.

Table 1 Components of composite joint.

Components			Elements
Inside of joint	Split tee		T-150×300×10×15
	Connecting element	Rod	Ø32 high tension rod
		Connecting plate	PL-19
	Structural angle		L-100×100×10
Outside of joint	Angle reinforced by a stiffener	Angle	L-150×150×15
		Stiffener	PL-16
	Web connection	Shear plate	PL-12
		High tension bolt	F10T M20
	Wide beam		H-400×200×8×13

the flexural moment of the beam. MR-1 and MR-2 specimens have the beam connected to the steel rods, and MP-1 and MP-2 specimens have the beam connected to the connecting plates.

2.3 Computation of shear force

2.3.1 Structural angle reinforced by a stiffener

The flexural tension on the beam flange is transferred to steel rods through a structural angle welded onto the flange. Then, the moment and shear force are generated on the angle due to the eccentricity between the steel rods and the beam flange. Thus, the angle was reinforced with a stiffener of 16 mm in thickness to bear these forces. Then, Eqs. (1) and (2) were used to analyze the shear force for the T-shaped cross section formed by the stiffener and the structural angle.

$$T = \frac{M}{e} = \frac{Z_T \times f_t}{e} \tag{1}$$

$$T = V = (A_L + A_{st}) \times f_s \tag{2}$$

where, T is the flexural tension of the beam flange, and e is the distance of eccentricity. Z_T is the cross sectional coefficient of the T-shaped cross section formed by the structural angle reinforced with a stiffener. A_L and A_{st} are the cross sections of the angle, and the stiffener, respectively. f_t and f_s indicate the allowed tensile stress and shear stress on each steel member, respectively.

2.3.2 Steel rods

The performance of high strength steel rods to transfer the flexural tension of the beam flange is expressed in Eqs. (3) and (4) by considering the prying action due to tensile force and eccentricity.

$$T = A_{rod} + F_{rod} \tag{3}$$

$$(T)' = T \times (1 - 0.2\sqrt{e}) \tag{4}$$

where, A_{rod} is the cross section of the steel rod, and F_{rod} is the tensile force. Additionally, $(T)'$ and e are the bearing force of the steel rod subjected to eccentric tensile force and the distance of eccentricity, respectively.

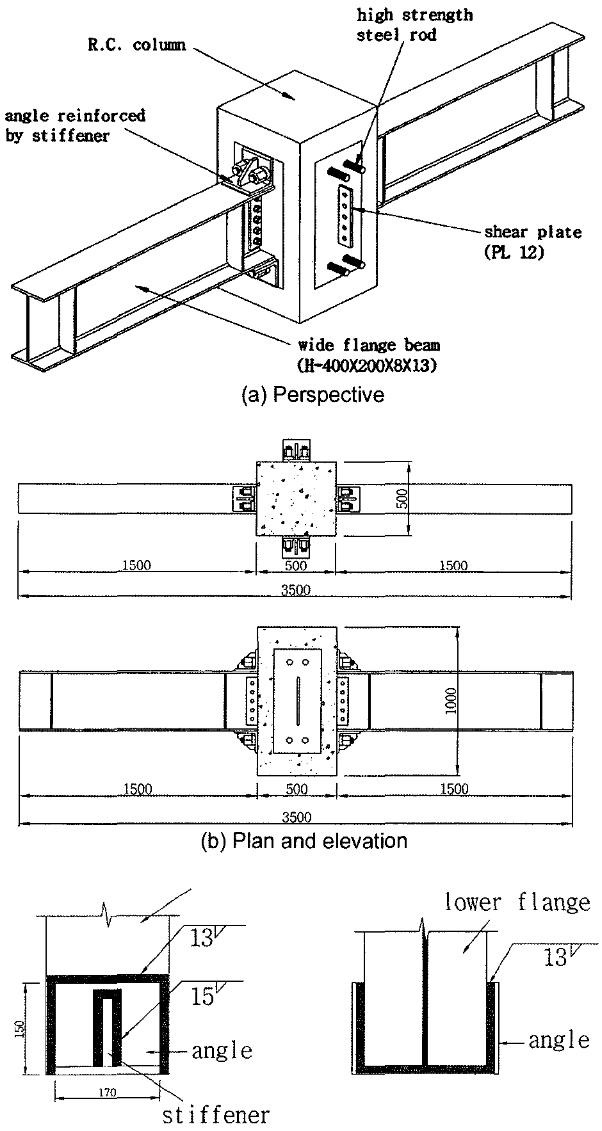
2.3.3 Connecting plates

The steel plate connected to the beam flange to transfer the tensile force of the flange is subject to flexural moment due to the tensile force of the beam flange and the eccentric force of the steel rod and the connecting plate. However, if the flexural strain of the connecting plate is satisfactorily restrained by the confinement force of the concrete placed inside the concrete column, it can be assumed that the connecting plate is subjected to tensile force only. The conditions for the concrete column to restrain the connecting plate can be obtained by the balance of power for the idealized model as depicted in Fig. 3 with the assumption of uniformly distributed loads on the connecting plates.

$$\frac{q_c l^2}{2} \geq Te \tag{5a}$$

$$Q_c = q_c l \geq \frac{2Te}{l} \tag{5b}$$

Here, the sum of vertical loads to restrain the deformation of the connecting plate, Q_c, can take into account of the axial force of the column and the tensile force of the columnar main rebar, etc. However, in consideration of the simplicity of the analysis



(a) Perspective

(b) Plan and elevation

(c) Welding detail between beam flange and angle

Fig. 2 Details of specimen.

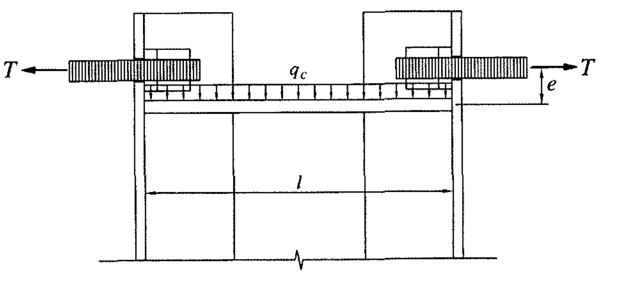


Fig. 3 Applied load on connecting plate.

and safety, it can be expressed as follows with the assumption that the tensile force of the concrete only is enough to confine the connecting plate.

$$Q_c = f_r \times A_c \tag{6}$$

where, f_r is the flexural tensile strength of the concrete, $2.0\sqrt{f_{ck}}$, and A_c is the cross sectional area of the concrete column with the structural tees removed. Thus, the condition to confine the flexural strain of the connecting plate is given by the following equation, where T_f is defined as the tensile force of the beam flange transferring to the steel rod.

$$T_f = \frac{f_r A_c}{2le} \tag{7}$$

When the condition of Eq, (7) above is satisfied, the resisting force of the connecting plate can be obtained by the tensile force of the beam flange only. Then, the allowed tensile bearing force, N, of one connecting plate is given by Eq. (8) below, where A_{con} denotes the cross sectional area of the connecting plate.

$$N = T_f = A_{con} \times f_t \tag{8}$$

Table 2 is the result of computing the resisting force of the connecting plate of the test specimen obtained through the above computational procedures. Here, the computed resisting force of the structural components of the proposed composite joint system has been replaced by the moment exerted on the joint and actual applied loads of the structural test equipment in order to make the comparison of the shearing force of the each component easier. Eq. (9) expresses the relationship among the applied load, moment at the joint, and tensile strength in the direction of the beam flange.

2.4 Loading and measuring methods

The structural test equipment was of 200 ton capacity, and vertical loading was applied to the center area of the concrete column of the test specimen as shown in Fig. 4(a), and flexural moment of $Pl/2$ and shearing force of $P/2$ were exerted to the joint (connection) area as shown in Fig. 4(b). Again, Eq. (9) below shows the relationship among the applied load of the structural test equipment, P, and the moment at the joint, M, and the tensile strength in the direction of the beam flange, T. Here, h is the depth of the beam, and t_f is the thickness of the flange.

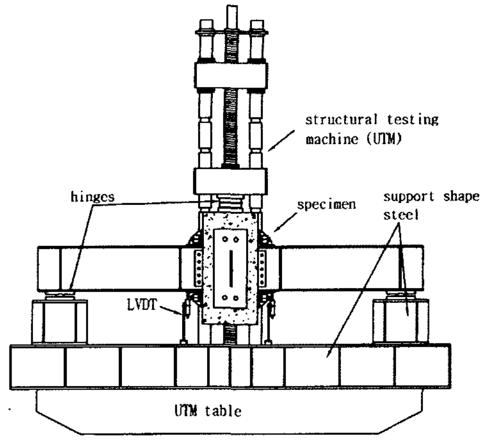
$$M = \frac{Pl}{2} = T \times (h - t_f) \tag{9a}$$

$$P = \frac{2T(h - t_f)}{l} \tag{9b}$$

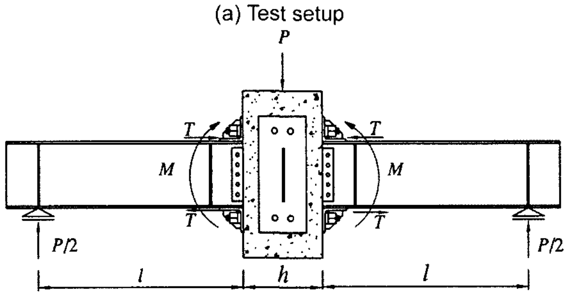
LVDT was installed at the bottom part of the test specimen to

Table 2 Design and applied load for components of specimen.

Components		Design load		Applied load	
		Allowable load	Yield load	P_a	P_y
Beam (H-400× 200× 8× 13)	Moment (*tf* · *m*)	24.15	36.23	37.15	55.73
Stiffened angle (L-150× 150× 15)	Shear (*tf*)	20.54	30.80	31.61	47.41
	Moment (*tf* · *m*)	13.17	19.76	20.28	30.42
Tension rod (Ø32, 2 ea.)	Tension (*tf*)	56.03	84.04	86.21	129.3
	Moment for prying action (*tf* · *m*, e = 5.45 cm)	29.87	44.80	45.95	68.92
Connecting plate (PL-19, 2 ea.)	Tension(*tf*)	24.71	37.06	38.01	57.02

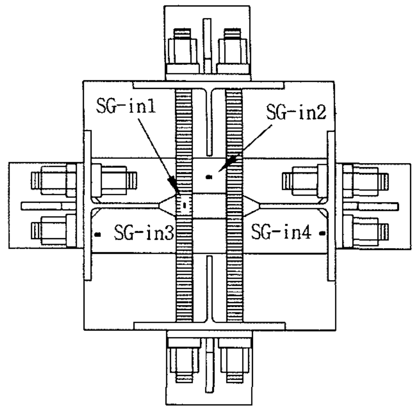


(a) Test setup

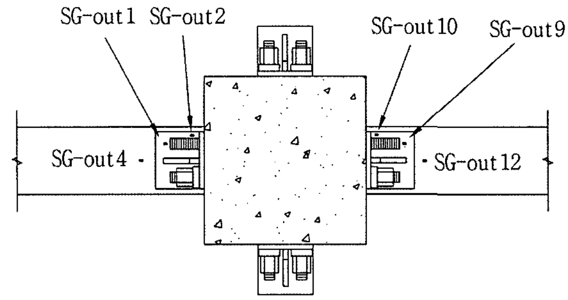


(b) Applied loads on specimens

Fig. 4 Test setup and applied loads on specimen.



(a) Inside of joint



(b) Outside of joint

Fig. 5 Location of strain gauges.

measure the deflection, and strain gauges were installed on the beam flange, the angle, the steel rods, and connecting plates, etc. The loading history was such that MR-1 and MR-2 test specimens were subjected to three times loading and unloading of 30, 50, and 70 tons in consideration of the maximum shear force at the joint. MP-1 and MP-2 test specimens were subjected to additional loading of over 80 tons to observe the plastic deformation behavior and the final destruction pattern.

3. Experimental results and discussion

3.1 Failure pattern

The loading continued until the tensile side of the beam flange entered the plastic state. However, the components inside the joint of the composite connection system did not exhibit a complete fracture. The deformation of the angle welded to the beam flange to spilt open outside of the column was observed, but there was no shear failure at all. Additionally, all test specimens exhibited softening of the strain for every 5~10 ton increase in the load past 50 tons. This is construed due to the slip phenomenon around the high strength bolts at the joint caused by the flexural stress distribution of the cross section.

3.2 Structural performance of flexural moment transfer elements at the joint

3.2.1 Structural angle

The structural angle, which transfers the tensile force of the beam flange to steel rods, is subject to the moment caused by the eccentricity of the steel rod center and the shear force generated by the tensile force of the beam flange. The result of the experiment showed that the structural angle was confined by flexural strain because of its short eccentric distance and closeness to the T-type reinforcement (structural tees). Thus, it was found that the maximum load was determined by shear force as shown in Fig. 6. In Fig. 6, the subscript, v, designates the applied load computed by the shear resisting force of the structural angle, and the subscript, *m*, denotes the load computed by the flexural resisting force. Additionally, P_a and P_y denote the allowed load and yield load, respectively, and table 2 summarizes these values for each component. In the figure, the structural angle showed almost linear behavior up to the yield shear force of $P_{y,v}$ = 47.41 tons. Thus, it is construed that the structural angle has a good capability for the load bearing.

The comparison of strain by various location of the structural angle indicated that the strain of SG 3 (strain gauge location 3) at the bending point of the angle was about twice greater than that

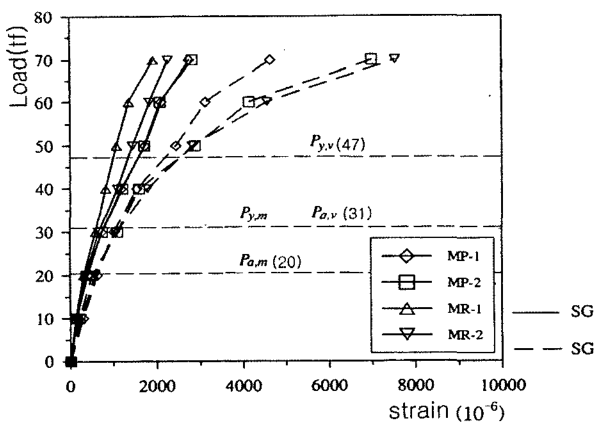


Fig. 6 Load versus strain curve for the angle.

of SG 2 at the center of the angle. Moreover, when the load was greater than 50 tons, the non-linear behavior of SG 3 was more conspicuous in the figure, indicating that the stress was concentrated on the bending point of the angle. In the Fig. 6, although values of the strain at SG 3 for MR-1 specimen was not obtained, it is presumed that it would have been very similar to the measuring values for other MR-type specimens.

3.2.2 Connecting plates

The connecting plates were initially thought to be subjected to the moment caused by the eccentricity with the steel rod and tensile force of the beam flange. However, it was found that the eccentric moment was restrained by the confinement force of the surrounding concrete and that only the tensile force exerted on them. Fig. 7 is the load-strain curve for the connecting plates and compares the strain of the center of the connecting plate of MP-1 and MP-2 test specimens to the result[4] of the direct tensile test of the connecting plate performed prior to this study. S19-1 and S19-2 are the test specimens for direct tensile test with the same thickness as MP test specimens. Here, the connecting plates of MP-1 and MP-2 test specimens exhibited a linear strain behavior in relation to the load up to the yield tensile load of $P_y = 57.02$ tons. However, the connecting plates of the specimens for direct tensile test (S19-1 and S19-2), which were not subjected to the concrete confinement effect, manifested a considerably poor structural performance. This attests for the confinement effect of the concrete used in this study.

3.2.3 Steel rods

Fig. 8 shows the process of transferring the flexural moment of the beam to the steel rod inside the joint of the composite structural system. In the figure, it can be seen that the strain of the steel rod is only about one half of the strain of the beam flange up to the yield tensile strength of 59 tons. Considering that two steel rods bear the tensile strength of the beam flange, the change in the strain of steel rods and the beam flange are almost the same, indicating a smooth flow of the stress. However, at the last stage of the loading test, a flexural deformation of the steel rods was observed due to the prying action of the steel rods and the structural angle.

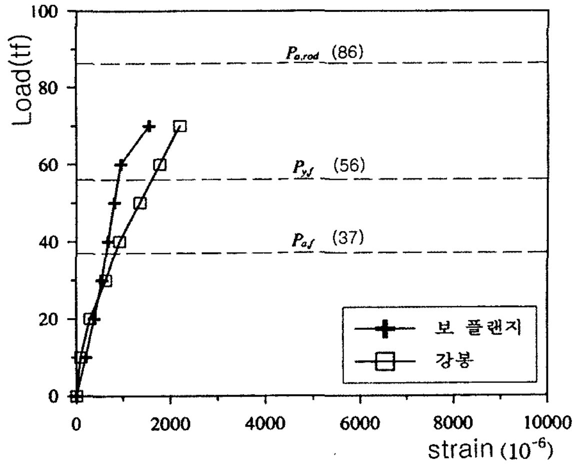


Fig. 8 Load versus strain curve for steel rod.

3.3 Deflection of the test specimen and moment-rotation angle curve

Fig. 9 shows the load-deflection curve for each test specimen, where P_a, P_y, P_p denote the short-term loads to generate the allowed, yield, and plastic moment, respectively, for each steel beam used. The deflection of the test specimen shows a linear behavior up to about 50 tons and non-linear behavior past this value of the load.

The MP-1 and MP-2 test specimens were also tested for the strain-deflection relationship with the load of 70 tons and additional loads over 70 tons afterwards. The result indicated that non-linear behavior became very conspicuous over the load of 70 tons and reached almost a plastic state. Considering the facts that the yield load, P_y, of the steel beam used in this study is computed to be about 55 tons and that the bearing force of the structural elements except the steel rods is computed to be about the same value as the steel beam or below, this deflection behavior of the joint area is construed to be very favorable and encouraging in terms of the structural efficiency and economic perspective. Moreover, it was found that the allowable load limit and the load bearing capacity for the composite frame joint was about 50 tons and about 70 tons, respectively. The moment-deflection angle curve of Fig. 10 shows a stable behavior to maintain the initial strength of all specimens fairly well up to the yield moment of the steel beam, $M_y = 38.34$ tonf·m. Nevertheless,

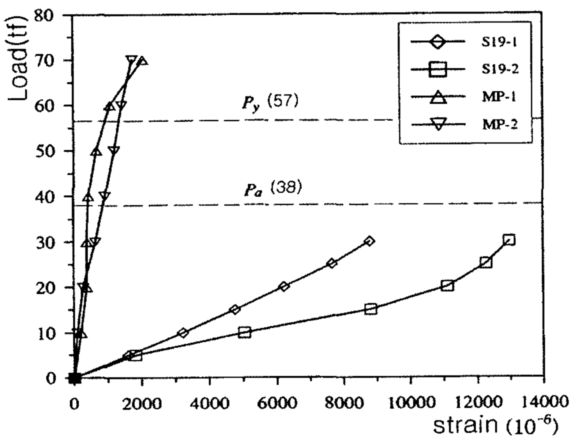


Fig. 7 Load versus strain curve for connecting plate.

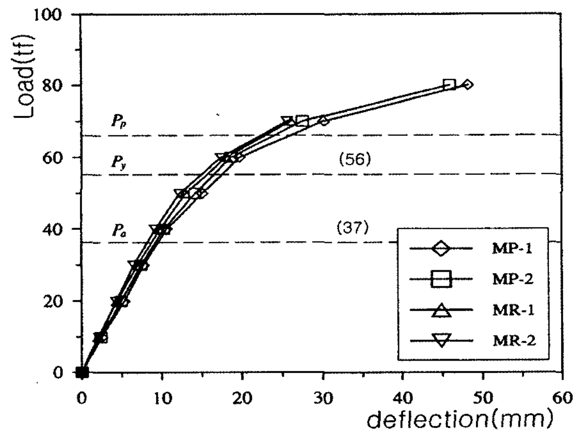


Fig. 9 Load versus deflection curve.

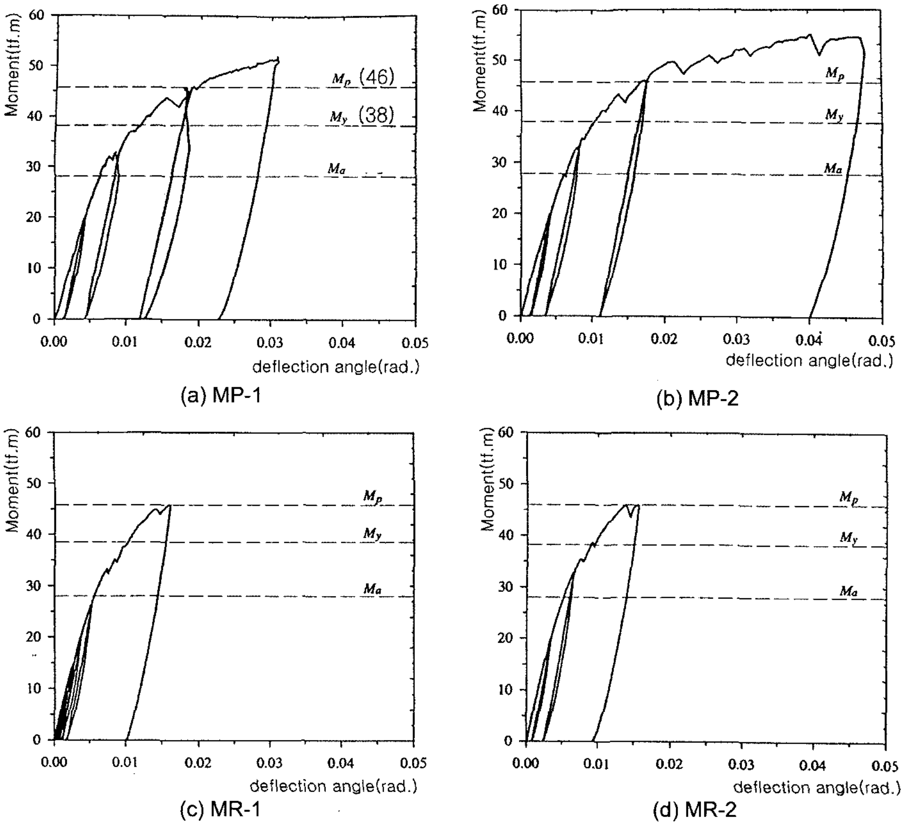


Fig. 10 Load versus strain curve for steel rod.

as the moment of the steel beam increased beyond the yield moment, the steel beam began to exhibit a decrease in its strength and the corresponding non-linear curve. Examining the load-strain curve for MP test specimens as shown in Figs. 10(a) and (b), non-linear behavior is conspicuously observed at or over the plastic moment of the steel beam of $M_p = 46.01$ tonf · m, accompanied by typical plastic behavior and a major deformation. The result of comparing and analyzing the moment-deflection angle curve against the bearing capacity of the steel beam indicates the proposed composite structural system shows a stable behavior pattern and a major deformation upon reaching the ultimate load, thus revealing its joint system of high structural efficiency.

4. Conclusions

This study proposes a new type of composite frame system using structural tees with the purpose of developing such a composite structure to transfer the load on the beam at the joint of the R/C (reinforced concrete) column and steel beam as evenly and smoothly as possible. As for the bearing forces of the beam member, flexural moment transfer experiments were carried out to obtain the following conclusions.

1) The result of structural tests to investigate the flexural moment transfer path and mechanism for the proposed composite joint (connection) system indicated that the influence of eccentric moment between the beam flange and steel rods was not considerable based on the observation that the structural angle exhibited linear load-strain curve behavior up to the yield shear force of $P_{y,v} = 47.41$ tons.

2) The steel rods or connecting plates inside the joint of the proposed composite structural system are members bearing the flexural moment. Steel rods showed almost the same load-strain relationship as that of the beam flange up to the yield tensile strength of the beam flange, ie. 59 tons. The connecting plates were subjected to both the tensile force of the beam flange and flexural moment due to its eccentricity with the steel rods. However, they exhibited linear load-strain relationship up to the yield tensile load of the beam flange, ie. $P_y = 57.02$ tons. This attests for the fact that the concrete around the connecting plates restrained the moment strain.

3) The moment- deflection angle curve for the test specimens maintained the initial strength fairly well up to the yield moment of the steel beam, $M_y = 38.34$ tonf · m. Nevertheless, non-linear load-strain relationship was conspicuously observed at or over the plastic moment of the steel beam of $M_p = 46.01$ tonf · m., and the plastic deflection angle was about twice that of yielding.

4) During the preparation of the test specimen for this study, there were some concerns over the assembly, molding formwork, and placing of the concrete for their field construction and implementation. Hence, structural tees were chosen and proposed to be a part of the composite structural joint during this investigative process. They were subsequently affirmed of the field applicability, transportability, and construction workability. Moreover, the result of structural tests revealed an encouraging finding that the load transfer through the structural angle between the beam flange and steel rods or connecting plates was very smooth and even.

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