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STUDY ON PERFORMANCE AND PRACTICAL USE OF NEW BUILDING STRUCTURAL SYSTEM WITH STEEL PLATES AND CONCRETE (PLRC TECHNIQUE): THE STRENGTH EVALUATION METHOD OF LONGITUDINAL SLIP OF THE COLUMN

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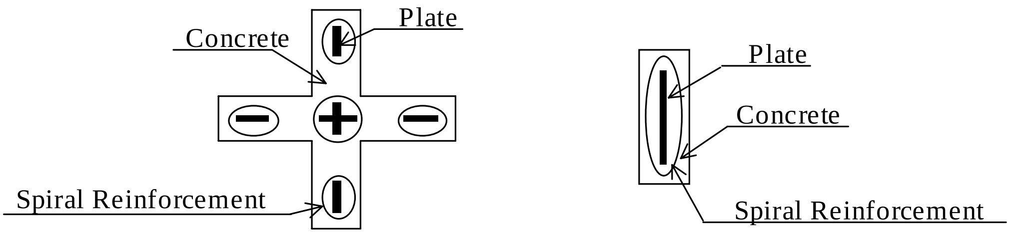
SUMMARY

We presented a new structural system - the Plate Reinforced Concrete (PLRC) technique, which is based on the use of precasting members that employ steel plates instead of reinforcing bars used in conventional reinforced concrete structural members –. However, *PLRC* column members have been confirmed through inverse symmetry loading tests of developing a rapid drop in strength caused by longitudinal slip failure - a phenomenon accompanied by longitudinal cracking in the axial direction of the member at the internal corners of the cross-shaped column section, unless a reinforcing plate (tie-plate) is installed at the central area of the member. This paper proposes a method for evaluating the longitudinal slip strength based on the failure mechanism discussed herein. It was confirmed that the longitudinal slip strength could be estimated by using the calculation formula based on the assumption that longitudinal slip failure occurs when the stress working at the internal corners of the section obtained by the Fiber Model becomes equal to the shear resistance of the concrete at that specific area.

INTRODUCTION

The *PLRC* technique aims at enhancing productivity of building materials for permanent houses through the industrialized precasting production of *PLRC* members - simple structural members consisting of concrete and steel plates -, and offering both spatial flexibility and rigidity, by utilizing the sectional configuration and purely rigid structure of the columns and beams. As may be seen from Fig. 1, the column and beam sections of the *PLRC* technique use plates in place of the main and shear reinforcements employed in reinforced concrete structures. The column section is a cross-shaped section whose width is equal to that of the beam. Repeated loading tests of column members conducted until now by the cantilever beam-loading system had revealed the properties of each specimen to be satisfactory [*Oya and Furuta, 1992*]. Hence, with a view toward bringing the state of stresses in the column members closer to that, which would be caused by actual seismic loads on the frame, the inverse symmetry loading system was adopted to confirm the structural performance.



(a) Column **(b) Beam**

Fig. 1: Section of column and beam

It was found that unless reinforcing plates (tie-plates) were installed to the central area of the column, longitudinal cracking would occur in the axial direction of the member at the internal corners of the cross-shaped

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section. Notably, in the specimens with large shear span ratios (*M/QD*=*1.75*:*C175S*), the column members were found to split longitudinally into three pieces along the longitudinal cracks following the occurrence of longitudinal cracking, eventually leading to brittle failure. To grasp the stress that would work on a tie-plate, which is expected to be capable of preventing longitudinal failure of the *PLRC* column members, this paper will examine the method for calculating the longitudinal slip strength, based on the longitudinal slip generating mechanism discussed herein. The mechanism was studied using, as the objects of study, the specimens that had undergone longitudinal slip failure.

GENERATION OF LONGITUDINAL SLIP FAILURE

Column specimens that had eventually resulted in longitudinal slip failure (Table 1) consisted of four members with shear span ratios (*M/QD*) ranging between 0.5 and 1.75, for which, no tie-plates were installed. For representative specimens (*C75S*, *C175S*), Fig. 2 shows the state in which longitudinal slip failure had occurred. In all specimens, flexural cracks occurred first in the column head and base areas at their boundary with the loading stubs. Then, diagonal cracks developed, running from the neighborhood of the center of the plate located on the outer side of the section toward the column center. Later, the direction of the diagonal cracks changed into the axial direction of the column member at the internal corners of the cross-shaped section. Maximum strength was reached at the point where longitudinal cracking became significant. For *C175S* – the specimen with a large shear span ratio (*M/QD*), it was confirmed that, at the point longitudinal cracking became significant, the edges of the plate located on the outer side of the section yielded in tension at the column capital and base, and the compression-side concrete crushed. By contrast, for *C50S*, *C75S* and *C100S* – specimens with a small *M/QD*, no yielding of plate, or crushing of concrete were confirmed. For all specimens, it was found that at maximum displacement, longitudinal cracking became significant and longitudinal slip developed along the longitudinal crack. The load and angles of member at generation of cracking, crushing, yielding of plate, etc. are shown in Table 1. For further details on the specimens, the reader is requested to refer to References [*Furuta and Yamamoto*, *1993*]. Fig. 3 shows the load-displacement hysterisis loops (*M-R*: *M*=Bending moment of critical section and *R*=Angle of member) for representative specimens (*C175S*, *C75S*). While the maximum strength of *C175S* – the specimen with a large shear span ratio (*M/QD*) – becomes equal to the flexural strength that of other specimens with small *M/QD* ratios was found to be lower than the flexural strength. In *C175S* whose *M/QD* is large, significant splitting (into three pieces) was observed in the axial direction of the member at maximum strength, due to longitudinal slip accompanied by longitudinal cracking. From there onward, strength deteriorated rapidly.

Table 1: Column members failed in longitudinal slip

Specimen (M/QD)	Yielding of plate (kN/R)	Crushing of concrete (kN/R)	Longitudinal slip (kN/R)	Ultimate load (kN/R)	Mode of failure
C50S (0.50)	264 1/140	254 1/250	255 1/300	289 1/100	Longitudinal slip
C75S (0.75)	166 1/150	186 1/250	182 1/300	192 1/200	Longitudinal slip
C100S (1.00)	137 1/150	145 1/150	161 1/500	161 1/500	Longitudinal slip
C175S (1.75)	127 1/200	138 1/150	130 1/150	138 1/150	Longitudinal slip

(Upper row: Generated load, Lower row: Angle of member)

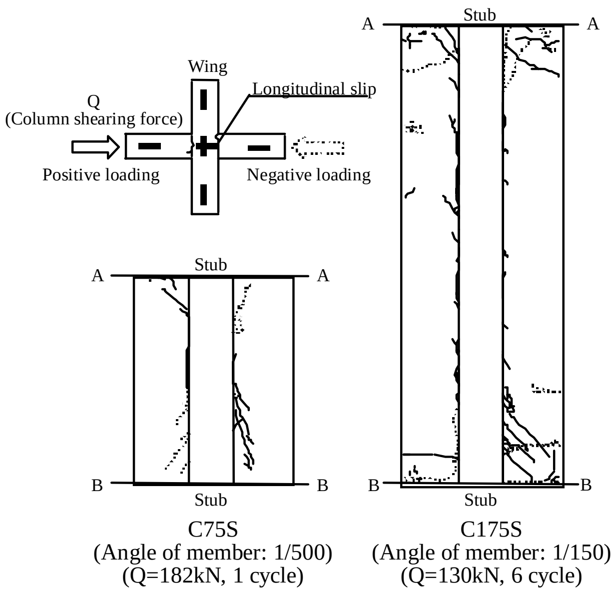
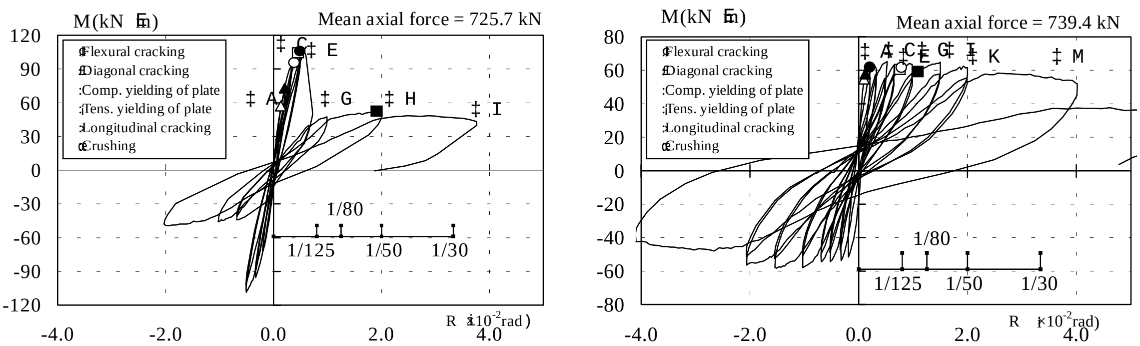


Fig. 2: Longitudinal slip failure



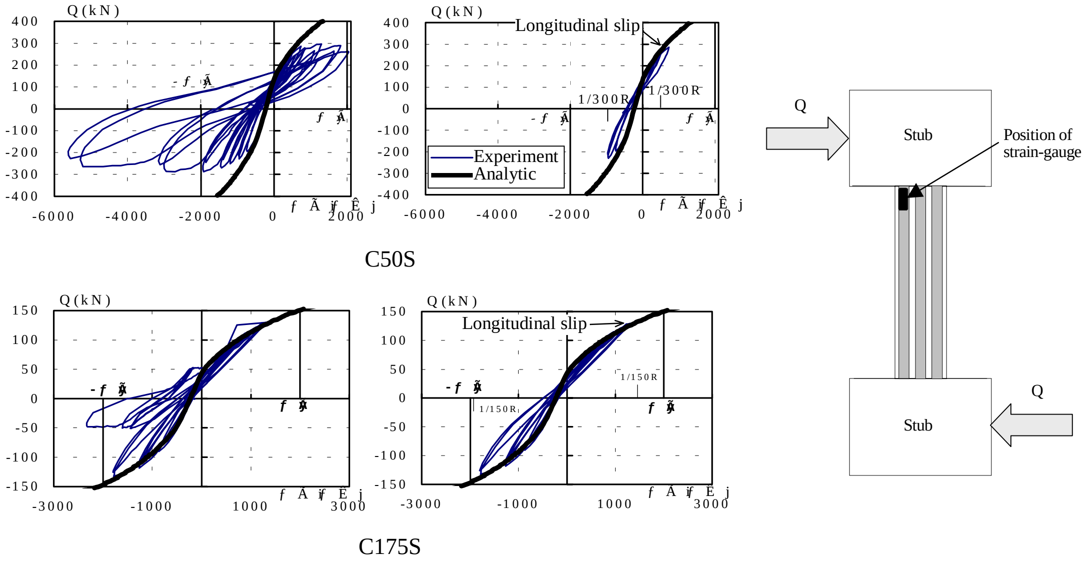
(a) C175S

(b) C75S

Fig. 3: Load-displacement hysterisis loop

RELATION BETWEEN PLATE STRAINS AND LONGITUDINAL SLIP PROPERTIES

For representative specimens (*C50S*, *C175S*), Fig. 4 (a) gives the load-strain (Q-ε : Q=Column shearing force) curve of the plate at the critical positions in the section illustrated in Fig. 4 (b). Fig. 4 (a) compares measured plate strains with calculated strains obtained by bending analysis, the fine lines representing experimental values, and the bold lines, calculated values. In the figure, the left-side graphs were plotted for the whole number of cycles, whereas, the right-side ones were plotted up to the number of cycles within the experimental and calculated values show agreement. Here, bending analysis was conducted by the Fiber Model based on the supposition that Bernoulli-Euler's assumption (plane retention) would hold. It was also assumed that the stress-strain relation of concrete would conform to the e-function system, and that the plates are perfect elastoplastic members who are compressive and tensile yield stresses are equal. As may be seen From Fig. 4 (a), the experimental and calculated values start to show disagreement when reaching the number of loading cycles (angle of member) where longitudinal cracking becomes significant. This is thought to be due to the fact that Bernoulli-Euler's assumption of plane retention no longer holds as not only has longitudinal slip caused the column member to split into 3 pieces along the longitudinal crack, but also because the plates start to develop some curvature. Since the time of longitudinal crack generation coincides with the point where the plate strain starts to disagree with the calculated flexural value, it is assumed that the longitudinal slip strength has been reached at the point where longitudinal cracking becomes significant. While in specimens with a small shear span ratio (*M/QD*), a slight rise in strength was observed even after longitudinal slip failure, specimens with a large *M/QD* (*M/QD*=1.75) were characterized by a rapid deterioration of strength following longitudinal slip failure.



(a) Load-strain curve of steel plates **(b) Position of strain gauge**

Fig. 4: Load-strain curve of steel plates and position of strain gauge

EXAMINATION OF EVALUATION METHOD FOR LONGITUDINAL SLIP STRENGTH

From the foregoing investigation, it was confirmed that longitudinal slip failure accompanied by longitudinal cracking occurs at the point where longitudinal cracking has further progressed and becomes significant, namely, the point where the plate strain measured at the critical positions of the section no longer shows agreement with the calculated strains obtained by the Fiber Model that postulates that Bernoulli-Euler's assumption of plane retention holds. Here, based on the longitudinal slip generating mechanism, confirmed through the phenomena as described above, the evaluation method for the longitudinal slip strength will be studied for the slip phenomenon, which is accompanied by longitudinal cracking at the internal corners of the cross-shaped section.

Hypothetical Conditions

First, in consideration of the experimental results obtained, the longitudinal slip resistance mechanism – the mechanism that forms the basis for evaluating the longitudinal slips strength – must satisfy the following conditions. (1) The direction of diagonal cracks that occur in the column capital and base areas is that of diagonal lines connecting opposite corners of the column capital and base. (2) The portion where longitudinal slip occurs is that at the internal corners of the column's cross-shaped section. (3) As may be seen from the load-displacement curves shown in Fig. 5, the smaller the shear span ratio (*M/QD*), the higher the longitudinal slip strength and maximum strength will become, with strength deterioration after maximum strength is reached becoming less rapid. (4) The state of stresses in the column capital and base areas up to longitudinal slip failure agrees with the results of bending analysis, which postulates that Bernoulli-Euler's assumption of plane retention holds. Fig. 6 (a) shows the external forces that act on the column member, together with the related state of stresses caused by sectional forces at the column capital and base positions. Meanwhile, Fig. 6 (b) illustrates the column member's resistance mechanism in opposing external forces. Let us assume here that longitudinal slip occurs at the *n-m* (*n'-m'*) surface, and the mode of failure is shear slip. That is, it is supposed that the shear stress of concrete at the failure surface (*n-m*) has reached the level (τ) at which shear slip takes place. Let us further assume that the longitudinal (axial) shearing force (Q_F) acting on the longitudinal slip surface (*n-m*) is the sum of the vertical component (C_{C2}) of the concrete compression strut, the compressive stress (C_S) of the plate in the compression zone, and the tensile stress (T_S) of the plate in the tension zone. Here, the tensile force of concrete is to be ignored. Meanwhile, of the vertical component (C_C in Fig. 6 (a)) of the concrete compression strut, the compressive stress (C_{C1} in Fig. 6 (b)) in the orthogonal loading area (wing area) of the column's cross-shaped section is ignored, since it is balanced within the wing area and is considered as having no influence on longitudinal slip. Hence, if, in determining the strut width (l_0 in Fig. 6 (b)…hutch area) of the concrete strut of equivalent compressive stresses, the size of the compressive zone (position of neutral axis: X_n) is found to extend as far as the wing area, the matter is to be examined within the compressive stress range (C_{C2}) up to the wing area. From the above assumptions, for the case where the shear surface *n-m* (*n'-m'*) undergoes longitudinal slip failure, the time at which longitudinal slip failure accompanied by longitudinal cracking occurs will be $Q_F > Q_R$, where, Q_R represents the shearing resistance acting in the longitudinal (axial) direction of the member.

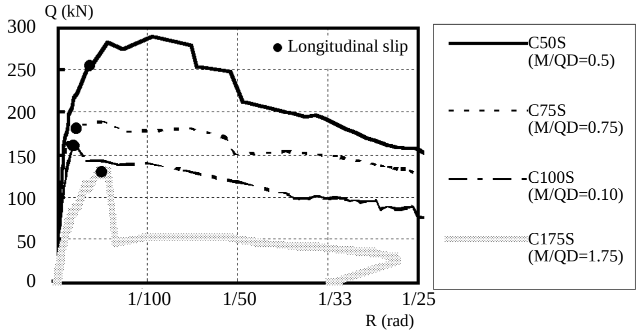
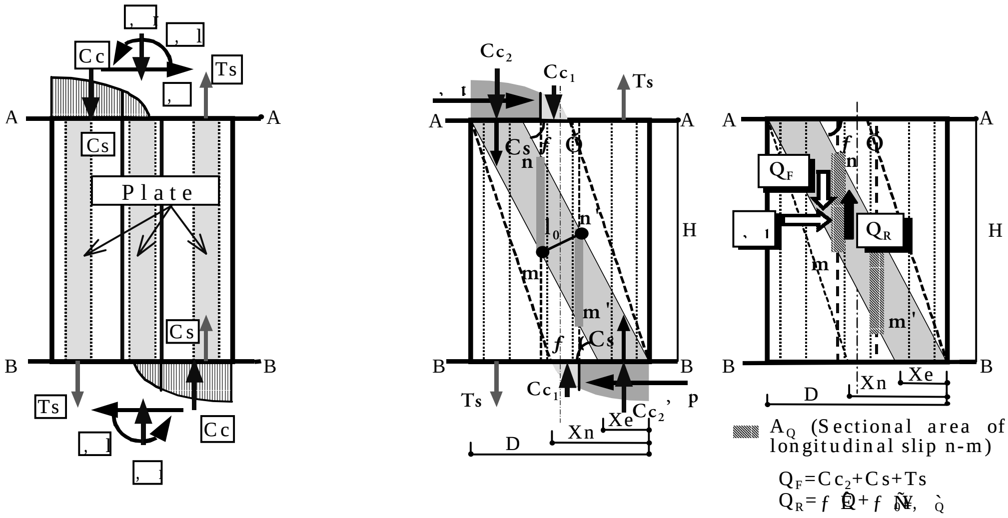


Fig. 5: Load-displacement curve



(a) Forces acting on the column **(b) Resistance mechanism**

Fig. 6: Forces acting on the column and resistance mechanism

Induction of evaluation formula for (longitudinal cracking-accompanied) longitudinal slip strength

The shear stress of the longitudinal slip surface upon the occurrence of longitudinal slip is obtained as follows: First, the compressive stress (σ_N) - shear stress (τ) relation of concrete is obtained from Eq. (2) using the coefficient (μ) which is equivalent to the frictional coefficient of concrete. At the same time, the pure shearing strength (τ_0) of concrete is obtained from Eq. 1 – the formula proposed by Gaston, et al. for obtaining the shear strength (V_U) of mortar joints (bonded joints) subjected to compressive stress [*Gaston and Kriz, 1964*].

$$V_u = 7.7 + 0.7 \cdot \sigma_N \quad (1)$$

Here, from the above formula, Eq. 2 is derived by using the empirically obtained 7.7 kgf/cm^2 as the pure shearing stress of concrete (τ_0), and 0.7, the coefficient of compressive stress (σ_N), as the frictional coefficient (μ).

$$\tau = \mu \cdot \sigma_N + \tau_0 \quad (2)$$

Since the compressive stress (σ_N) is that caused by the horizontal shear force (Q) applied by the concrete compression strut and is expressed by Q/A_Q – the value obtained by dividing Q by the longitudinal slip area (A_Q), Eq. 2 may be written as

$$\tau = \mu \cdot (Q / A_Q) + \tau_0 \quad (3)$$

where, for the frictional coefficient μ, μ =0.8 as proposed by [*Mattock and Hawkins, 1972*] has been adopted.
σ_N: Compressive stress acting on concrete, μ: Frictional coefficient (=0.8) [*Mattock and Hawkins, 1972*], τ_0: Pure shear strength of concrete (=0.088σ_B+63.4) [*Watabe, 1987*], σ_B: Compressive strength of concrete, Q: Horizontal shearing force, A_Q: Longitudinal slip area.

Next, the sectional area (A_Q) of the longitudinal slip-shearing surface (*n-m*, *n'-m'*) is obtained from the following equation.

$$A_Q = \{H - (D/2 - X_e \cdot \tan\phi \cdot 2)\} \cdot B \tag{4}$$

And, since $\tan\phi = H/(D-X_e)$, Eq. (4) can be written as

$$A_Q = X_e \cdot B \cdot H / (D - X_e) \tag{5}$$

where, H: Column height, D: Column width, B: Column depth, ϕ: Angle of axial line (>45º), X_e: Length of compression block for determining width of equivalent compressive-stress strut (l_0).

Fig. 7 illustrates the failure conditions of the joint surface, expressed by the compressive (axial) stress (σ_N) – shear stress (τ) relation, based on the stress transfer mechanism at the contact surface of the concrete joint. The right-side graph in the figure shows that the mode of concrete failure changes from slip failure to compression failure at the boundary surface when the σ_N-value becomes greater than the τ-value. That is, it can be expected that, in longitudinal slip failure discussed in this paper, too, the mode of failure will change from longitudinal failure to compression failure of concrete when σ_N becomes greater than τ. Since the mode of concrete failure will be slip (longitudinal slip) when the angle of the concrete strut to the longitudinal slip surface is less than 45º (which makes σ_N smaller than τ), the range of the strut angle to the longitudinal surface, i.e. , the aforementioned angle of axial line (ϕ) was set to >45º. With reference to Eqs. (4) and (5), it is believed that the strut width (l_0) for equivalent stresses would vary depending on the difference in the shear span ratio (*M/QD*). For the four specimens, who had undergone longitudinal slip failure, Fig. 8 (a) shows the state of concrete stresses at the column capital and base obtained through bending analysis for the time of longitudinal slip failure. As may be seen from this figure, for all specimens, not only does the compression zone, i.e., the position of the neutral axis (X_n), extend as far as the wing area upon the generation of longitudinal slip, but the state of concrete stresses differs from specimen to specimen as well. Accordingly, in this paper, the length of X_e, as shown in Fig. 8 (b), was set to a block length obtained by replacing the (C_{C2}) area (the compressive stress area at the column section's wing area where (C_{C1}) is ignored) with an equivalent-stress block obtained on the basis of the compressive unit stress (σ_m) of concrete that occurs at section edges. Furthermore, it was decided that, when σ_m becomes equal to the compressive strength of concrete (σ_B), the effective length of the stress block (X_e) is to be multiplied by the effective coefficient (β=0.85). Here, the compressive strength of concrete is set to the range of σ_B < 28MPa. Based on the above assumptions, when the shear surface (*n-m*, *n'-m'*) undergoes longitudinal slip failure, the shear strength (Q_R) may be expressed as

$$Q_R = \tau \cdot A_Q = \mu \cdot Q + \tau_0 \cdot A_Q = \mu \cdot Q + \tau_0 \cdot \beta \cdot X_e \cdot B \cdot H / (D - \beta \cdot X_e) \tag{6}$$

where, $\sigma_m < \sigma_B$: β=1.0, $\sigma_m = \sigma_B$: β=0.85

And, from the assumption that the shearing force (Q_F) acting on the shear surface (*n-m*, *n'-m'*) is the sum of the vertical component of the concrete compression strut, the compressive stress (C_S) of the plate in the compression zone, and the tensile stress (T_S) of the plate in the tension zone, the shearing force (Q_F) may be written as

$$Q_F = C_{C2} + C_S + T_S \tag{7}$$

Hence, the strength at generation of longitudinal slip failure accompanied by longitudinal cracking may be expressed, from the failure condition, $Q_F > Q_R$, as Eq. 8.

$$Q = \{C_{C2} + C_S + T_S - \tau_0 \cdot \beta \cdot X_e \cdot B \cdot H / (D - \beta \cdot X_e)\} / \mu \tag{8}$$

Therefore, the shearing force (Q) at longitudinal slip failure ($Q_F > Q_R$) accompanied by longitudinal cracking can be obtained through bending analysis conducted by the Fiber Model adopted in Eqs. (6) and (7). More specifically, as may be seen from Fig. 9, the longitudinal slip strength (Q_{cal}) is the value obtained at the intersecting point where $Q_F > Q_R$, when Q_R (Eq. 6) and Q_F (Eq. 7) are taken on the axis of ordinates and Q on the axis of abscissas.

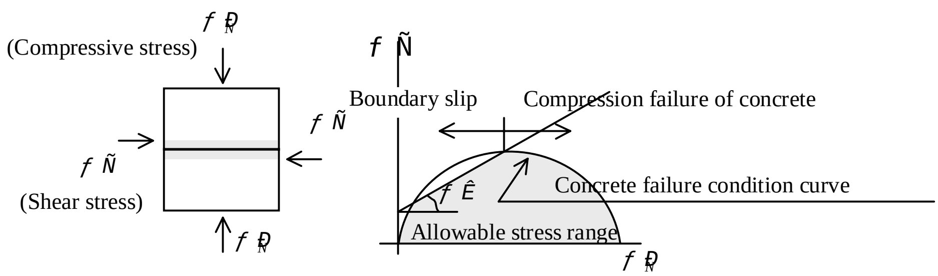
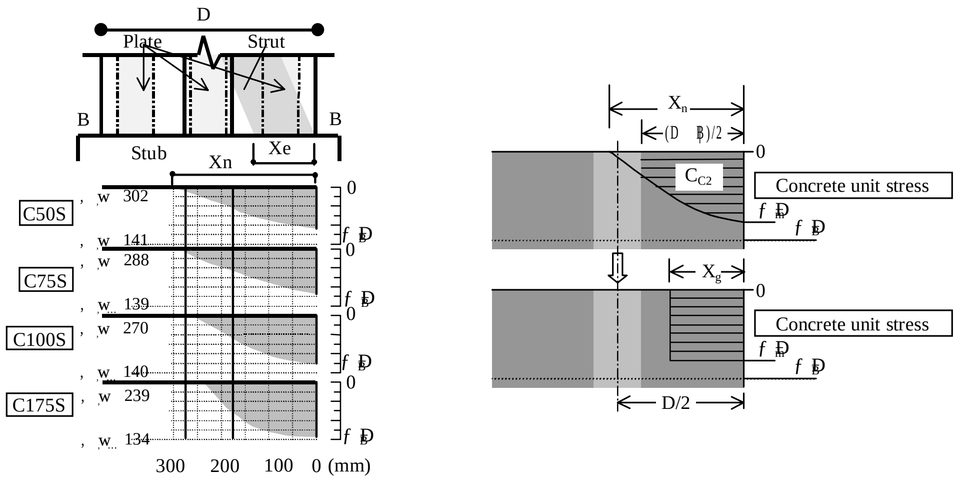


Fig. 7: The concept of compressive stress transmission



(a) Stress state chart of concrete on column capital and base at longitudinal slipping failure **(b) Equivalent strut width**

Fig. 8: Stress state chart of concrete and equivalent strut width

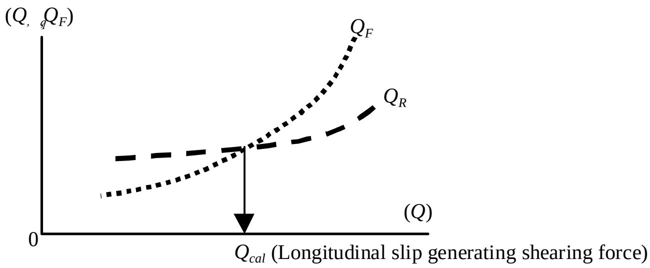


Fig. 9: Relations between the shearing stress (Q_F) and the resistance strength (Q_R)

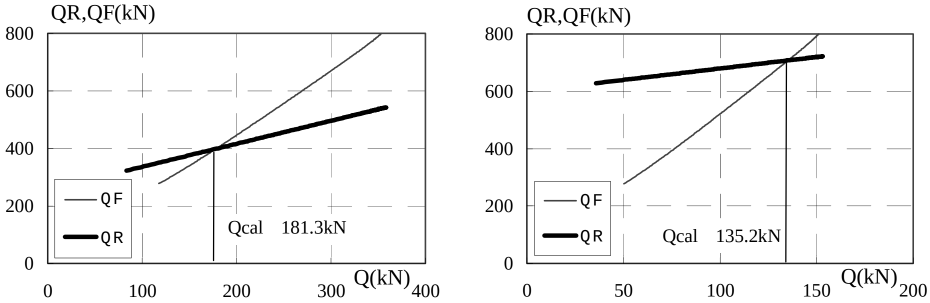
EXAMINATION OF ANALYTICAL RESULTS

For the four specimens, who had undergone longitudinal slip failure as a result of inverse symmetric loading, Table 2 compares the longitudinal slip generating strength (Q_{cal}) obtained from Eqs. (7) and (8) with the longitudinal slip-generating load obtained through experiments. Also shown in the table are, the block length (X_e) by which the width of the equivalent-stress strut (l_0) is determined, as well as the vertical component (C_{C2}) of the concrete compression strut, the compressive stress (C_S) of the plate in the compression zone, and the tensile stress (T_S) of the plate in the tension zone. Meanwhile, Fig. 10 illustrates the relation of Q_F and Q_R with Q. As may be seen from Table 2, the experimental and calculated values agree with each other with excellent accuracy. This shows that it is highly possible to estimate the longitudinal slip generating strength by using the evaluation method proposed herein. The method, which is based on the mechanism of longitudinal slip generation accompanied by longitudinal cracking in the column member discussed earlier, assumes that shear slip failure occurs at the longitudinal slip surface, and also that the shear stress working on the longitudinal slip surface is the sum of the vertical component of the concrete compression strut, the compressive stress of the plate in the compression zone, and the tensile stress of the plate in the tension zone.

Table 2: Comparing analytical results with experimental results

Specimen	Experiment	Analytic					Q_L/ Q_{cal}
(M/QD)	Q_L	X_e	C_{C2}	C_S	T_S	Q_{cal}	
C50S (0.50)	255	141	297	61	21	261	0.98
C75S (0.75)	182	139	312	66	27	181	1.00
C100S (1.00)	161	140	351	82	45	161	1.00
C175S (1.75)	130	133	435	134	111	135	0.96

(Q_L, C_{C2}, C_S, T_S, Q_{cal}: kN, X_e: mm)



(a) C75S **(b) C175S**

Fig. 10: Relations between Q_F and Q_R

SUMMARY

With a view toward grasping the stresses that would work on a tie-plate that could be expected to prevent longitudinal slip failure that would otherwise occur in *PLRC* column members at the internal corners of the cross-shaped section in the axial direction of the member, the evaluation method for longitudinal slip strength has been examined in this paper. From the experimental results obtained, it was confirmed that the hypothetical conditions to be set for studying the resistance mechanism to longitudinal slip would be as follows: (1) The direction of diagonal cracking that occurs in the column capital and base areas would be in the direction of the diagonal lines connecting opposite corners of the column capital and base. (2) The area where longitudinal slip occurs would be the internal corner of the cross-shaped section of the column. (3) The smaller the shear span ratio (*M/QD*), the greater the longitudinal slip strength and maximum strength will become, with strength deterioration after maximum strength is reached becomes less rapid. And, (4) the state of stresses occurring in the column capital and base areas up to longitudinal slip failure agrees with the results of bending analysis conducted on the basis of Bernoulli-Euler's assumption of plane retention. Based on the hypothetical conditions, a calculation formula for estimating the longitudinal slip strength was established, which assumes that the stress working on the longitudinal slip surface is the sum of (1) the vertical component of the concrete compression strut obtained by the Fiber Model, (2) the compressive force of the plate in the compression zone, and (3) the tensile stress of the plate in the tension zone. Meanwhile, the resistance at the longitudinal slip surface was assumed to be the shear resistance of concrete subjected to compressive axial stress. As a result, it was confirmed the calculated results showed excellent agreement with the empirical results. It was thus confirmed that the longitudinal slip strength of *PLRC* column members can be estimated by using the proposed calculation formula – a formula based on the assumption that longitudinal slip failure occurs when the stresses working at the internal corners of the cross-shaped section obtained by the Fiber Model becomes equal to the shear resistance of concrete of that specific area. Due to the successful the successful results obtained in calculating the longitudinal slip strength, the authors believe that it is highly possible to estimate the stresses that work on a tie-plate that could be expected to prevent longitudinal slip failure.

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