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Application of High Strength Steel to Composite Structures

Utilisation d'acier à haute résistance dans les structues mixtes

Verwendung von hochfestem Stahl in Verbundbauwerken

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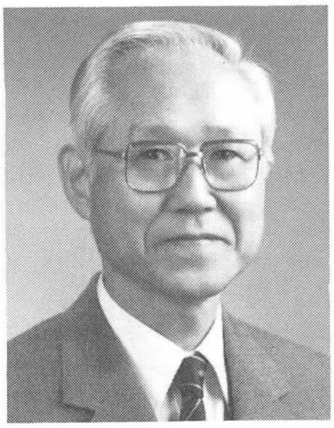

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SUMMARY

Use of high strength steel in concrete encased steel structures is thought to make them perform better, more earthquake-resistant, more economical, and more flexible in structural planning. This paper describes the outline of a research program conducted to promote the use of high strength steel in concrete encased steel structures. Problems to be resolved are identified, and major results obtained from individual tests programs, are presented. Procedures to estimate the strength of concrete encased steel members with high strength steel are also introduced in this paper.

RÉSUMÉ

L'emploi de l'acier à haute résistance dans les structures d'acier noyé dans le béton a été considéré en vue d'augmenter la résistance de ces ouvrages aux effets sismiques et d'établir des projets plus économiques et plus flexibles. L'étude décrit le programme de recherche destiné à promouvoir l'utilisation d'acier à haute résistance dans les structures d'acier noyé dans le béton. Elle donne les moyens d'identifier les problèmes et fournit la plupart des résultats obtenus à partir de séries d'essais. Elle introduit aussi la procédure d'estimation de la résistance des éléments de ce type de structure mixte.

ZUSAMMENFASSUNG

Die Verwendung von hochfestem Stahl in Verbundtragwerken soll diese wirtschaftlicher, erdbebenbeständiger und die Planung flexibler machen. Dieser Beitrag beschreibt ein Forschungsprogram zur Förderung der Verwendung von hochfestem Stahl in Verbundbauwerken. Die Resultate aus zahlreichen Versuchen werden, zusammen mit Bemessungsvorgehen für derartige Tragwerke, vorgestellt.

1. INTRODUCTION

Concrete encased steel (designated as SRC) structures have been widely used in Japan. Advantages of SRC structures are multiple; large ductility can be achieved thanks to ductile steel components, local buckling of steel plates are retarded significantly because of the confinement provided by surrounding concrete, and the cross section can be reduced because of steel's high strength, all of which make SRC structures effective particularly against earthquake loading. At the present time, in Japan, steel that can be used in SRC structures is limited to 520 MN/m^2 in strength, but use of steel having a higher strength has been expected to construct SRC structures higher, more economical, and also more flexible in structural planning. To lead a path to design and construct such SRC structures with high strength steel, we should resolve the following fundamental problem: i.e., whether or not combining steel having a larger yield strain with concrete whose yield strain is rather limited can still ensure full composite action in SRC structures? In order to promote the use of high strength steel in SRC structures, a three year comprehensive research project was conducted, and a research committee was organized to implement the project. The senior writer was Chairman of the committee, and nine research organizations participated in this project. This paper presents the background and objectives of the project, outline of the test programs, and major results obtained from the individual tests. This paper also proposes design procedures effective to the design of SRC structures with high strength steel.

2. AREAS OF RESEARCH NEEDED

Based on preliminary surveys, the following problems were identified to be resolved so as to promote the use of high strength steel in SRC structures.

Method to Estimate the Ultimate Strength: It is known that the ultimate strength of a SRC member with mild-steel can be estimated reasonably based on the stress versus strain relationships of the steel and concrete employed and by using the assumption that the plane section remains plane after deformation. We should check if this method is still usable for SRC members with a higher strength. In Japan, the superposed strength method has been employed to estimate the ultimate strength of a SRC member because of its simplicity and reasonable accuracy [1]. In this method, strengths of the steel and reinforced concrete components of a SRC member are computed separately, and the sum of the two strengths is taken as the strength of the member. Since high strength steel is significantly larger in the yield strain than normal mild-steel, it is important to check if this method is still applicable, without producing unsafe estimates of the strength, when high strength steel is used. The procedure to estimate the shear strength of a SRC member, also based on the superposed strength method, is another subject that needs calibration.

Evaluation of Ductility: Effects of the axial force imposed, width-to-thickness ratio of steel plates, and yield ratio (defined as the yield stress divided by the ultimate strength) of steel on the ductility of SRC members should be evaluated.

Reinforcing Effective to SRC Members: Reinforcing details that are effective in structural performance as well as handy in construction should be established.

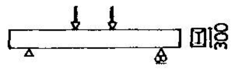
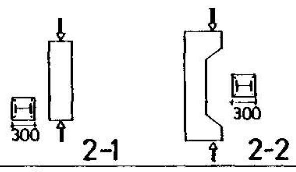
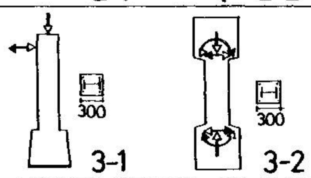
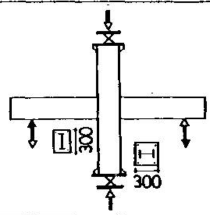
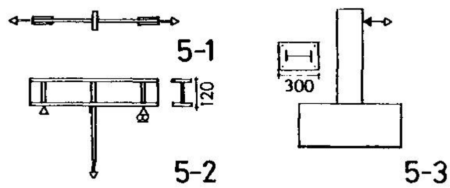
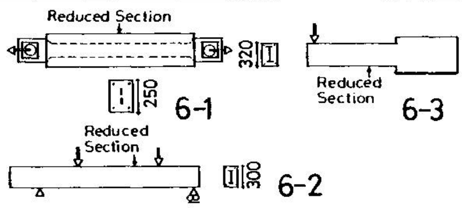
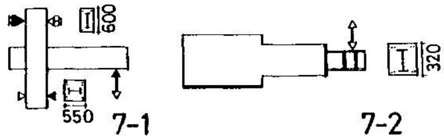
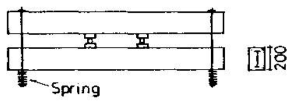
Connections Effective to SRC Members: Deformation capacity of a SRC member is likely to be reduced at its connections because of a relatively large yield ratio of high strength steel. Reinforcement to avoid premature failure at such connections should be established.

Long Term Deflection and Creep of SRC Beams: SRC beams with a long span-length are susceptible to excessive deflection and cracking. Range of long-term deflections and crack widths expected in SRC beams should be evaluated.

3. OUTLINE OF TESTS

Steel materials shown in Table 1 were chosen in this study. The ultimate strength was either 590 MN/m^2 (the main target in this study), 390 MN/m^2 (mild-steel used typically and for comparison purposes), and 780 MN/m^2 (very high strength steel also for comparison purposes), and three yield ratios: 0.7, 0.8, and 0.9, were selected. Table 1 lists the combination of the ultimate strength and yield ratio of the steel materials used in this study, including the designations of respective materials. Figure 1 shows stress versus strain curves of these materials. Normal concrete was used with the strength of either 20 or 29 MN/m^2. Table 2 summarizes the test programs, which include tests of steel and reinforced concrete members and connections for the sake of comparison. This table also indicates the number, shape, and dimensions of specimens tested in the respective test programs.

Table 2 Summary of Test Programs

ID of Test	Outline of Test		Number of Specimens SRC	Number of Specimens S(RC)	Dimensions of Specimen
0	Material Behavior		-	60	
1	Beams in Flexure		20	4	
2-1	Columns in Compression	Concentric Loading	20	11	
2-2		Eccentric Loading	30	-	
3-1	Columns in Axial and Shear	Failed in Flexure	22	12	
3-2		Failed in Shear	30	-	
4	Beam-to-Column Connections		9	7	
5-1	Ductility of Welded Connections	+-Shaped Connection(S)	-	12	
5-2		T-Shaped Connection(S)	-	15	
5-3		SRC Connection	12	-	
6-1	Ductility of Members in Reduced Section	in Tension	24	12	
6-2		in Uniform Moment	11	4	
6-3		in Moment Gradient	8		
7-1	Ductility of Connections with Reduced Section	Ductility Behavior Effect of Reinforcement	6	-	
7-2			6	-	
8	Creep Behavior of Beams		6	(2)	

4. TEST RESULTS

4.1 Beams

Tests were carried out for simply supported beams (shown in Table 2) with one way (monotonic) loading. Load versus deflection curves of SRC beams with high strength steel were found as stable as those of SRC beams with mild-steel, exhibiting large deformation capacity. Because significant portion of the steel component remained elastic at the maximum strength, the strength estimated by the superposed strength was larger than the experimental strength, but the discrepancy was at most 10 percent.

4.2 Columns in Compression

4.2.1 Columns Subject to Concentric Loading

The test results indicated that the superposed strength method is useful if the ultimate strength of steel is 590 MN/m^2 or smaller but provides an unsafe estimate when it is 780 MN/m^2. Strength degradation after reaching the maximum strength was observed less significant for columns with a higher ultimate strength.

4.2.2 Columns Subject to Eccentric Loading

Force versus deflection curves of SRC columns subjected to eccentric compression were approximately the same regardless of the type of steel, but strength degradation in the unstable range was more conspicuous for columns with a lower ultimate strength. As shown in Fig.2, the ultimate strength estimated by considering the compatibility of strain between the steel and concrete components is always smaller than the experimental strength, but the strength estimated by the superposed strength method is larger than the experimental strength for columns with steel whose ultimate strength is 780 MN/m^2. It was found that the superposed strength method needs amendment if it is to be employed for estimating the strength of a SRC column whose steel component has 780 MN/m^2 or larger in the ultimate strength.

4.3 Members Subjected to Constant Axial Force and Repeated Bending

4.3.1 Members Failed in Flexure

The tests showed that force versus deflection curves are stable as shown in Fig.3 unless the axial force imposed was very large. In Fig. 4, the skeleton curves of steel and SRC members are compared for steel: "47" and "89" (see Table 1 for notation). In steel: "89", the steel component yielded at the deflection twice the deflection corresponding to the crushing of concrete, which had resulted in a large portion of stable region designated as B in Fig.4(b). The superposed strength method was found applicable to those with steel having 390 and 590 MN/m^2 but provided an unsafe estimate for those with steel having 780 MN/m^2.

4.3.2 Members Failed in Shear

Force versus deflection curves of SRC members failed in shear are of typical Masing-type as shown in Fig.5. Figure 6 shows the skeleton curves of SRC members with steel: "47", "69", and "89". In this figure, $_{SRC}Q$ denotes the strength of the SRC member (obtained from the test), $_{S}Q$ the strength resisted by the steel component (which was estimated from measured strains), and $_{RC}Q$ the difference between $_{SRC}Q$ and $_{S}Q$ and taken as the strength resisted by the reinforced concrete component. The black circle shows the value of $_{RC}Q$ at the deflection corresponding to the maximum $_{SRC}Q$. This figure indicates that the steel component had yielded when the member reached the maximum strength. At the maximum strength, $_{RC}Q$ also reached its maximum for "47", but exceeded the maximum for "69" and "89". This observation suggests that the maximum strength of the SRC member is smaller than the sum of the maximum strengths of the steel and reinforced concrete components, thus invalidating the superposed strength method. To amend this discrepancy, a reduction factor (ϕr) may be introduced for estimating the strength of reinforced concrete component. The writers propose, for the value of this factor, 1.0, 0.9, and 0.7 for steel with 390, 590, and 780 MN/m^2 in ultimate strength respectively. In some tests, L-shaped hoops were used instead of typical rectangular hoops. No clear difference in behavior was observed between them, and full bonding was achieved up to the deflection corresponding to 8 x 10^{-3} in drift angle.

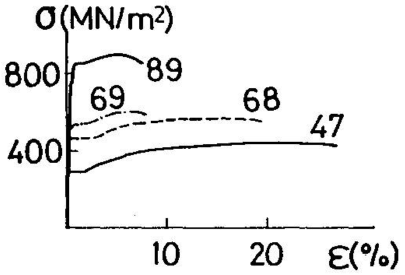
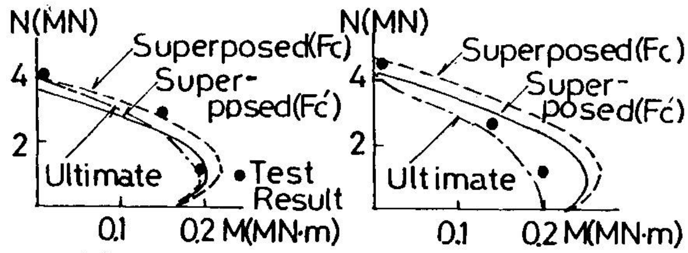


Fig. 1 Stress vs. Strain Curves of Steel



(a) Steel: 68

(b) Steel: 89

Fig.2 Columns Subject to Eccentric Loading

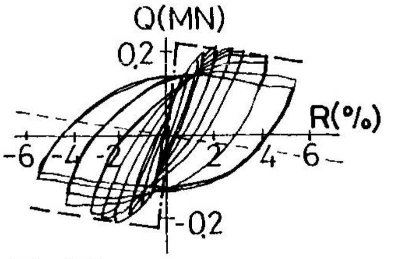
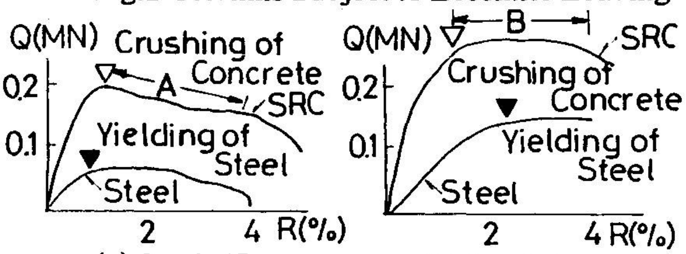


Fig.3 Response of Column Failed in Flexure



(a) Steel: 47

(b) Steel: 89

Fig.4 Skeleton Curves of Columns Failed in Flexure

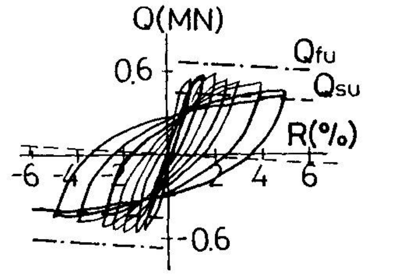
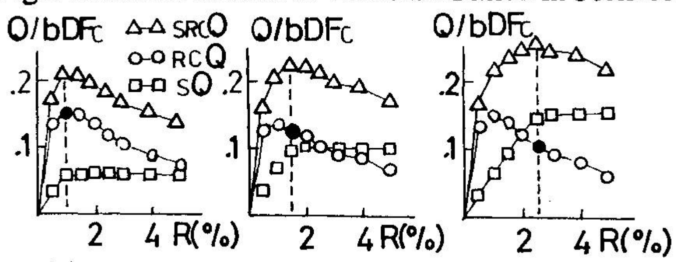


Fig.5 Response of Column Failed in Shear



(a) Steel: 47

(b) Steel: 69

(c) Steel: 89

Fig.6 Skeleton Curves of Columns Failed in Shear

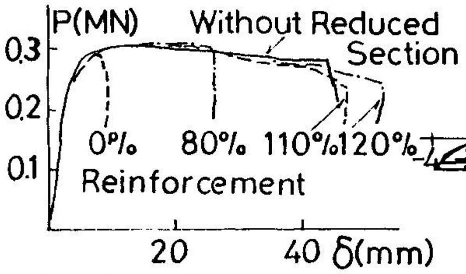
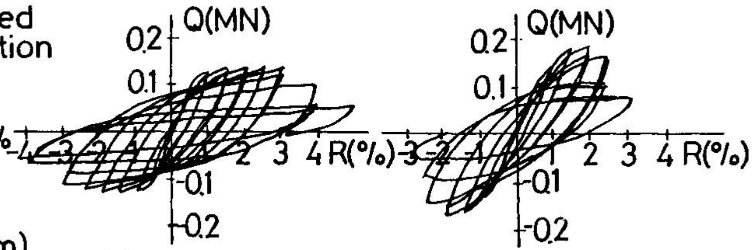


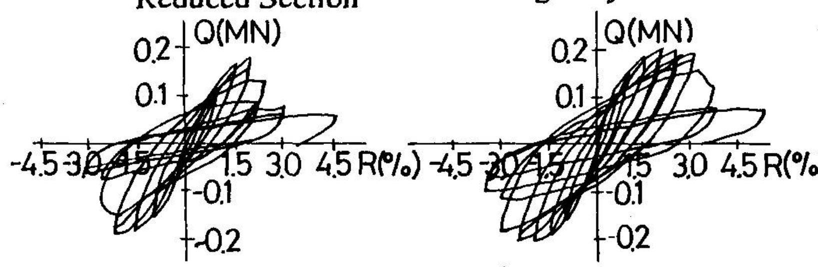
Fig.7 Ductility of Members in Reduced Section



(a) Steel: 47

(b) Steel: 69

Fig.8 Hystereses of Beam-to-Column Connections



(a) Without Reinforcement

(b) With Reinforcement

Fig.9 Effect of Reinforcement in Members With Reduced Section

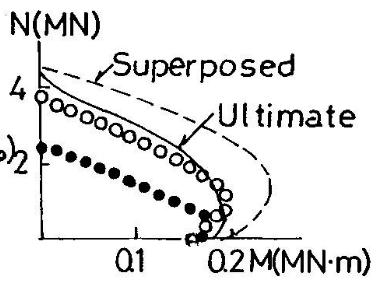


Fig.10 Amendment of Superposed Strength Method

4.4. Beam-to-Column Connections

Beam-to-column connections were tested in a repeated loading condition. Hysteresis curves obtained exhibited stable behavior regardless of the type of steel. Present design provisions for SRC connections [1] were found applicable to those with high strength steel.

4.5 Ductility of Members with Reduced Cross Section

Figure 7 shows force versus deflection curves of SRC beams subjected to uniform moment and having a section where the cross sectional area of the steel component was reduced by 50 percent. If the section was reinforced by reinforcing bars so that 80 percent of the strength that should have been resisted by the steel area removed was compensated for, strength of the section was fully recovered, and if it was reinforced by 110 percent, ductility of the section was also recovered. Furthermore, if the moment applied varied along the length, reinforcement by 120 percent ensured full recovery of both strength and ductility even under load reversals.

When the steel section was corped at the beam-end, it was found difficult to move the critical section where a plastic hinge occurs even with additional reinforcement. Figure 8 shows hysteresis curves of beam-to-column connections whose ends were corped. Ductility reduced when high strength steel was employed. If the corped section was reinforced by stirrups and additional U-shaped bars, ductility improved (Fig.9), but the member still failed in that section.

4.6 Creep Behavior of SRC Beams

Creep tests for SRC beams indicated that the creep coefficient remained unchanged even if high strength steel was employed. The long-term deflection of a SRC beam can be estimated by assuming it as an equivalent RC beam. As an alternative, the deflection can be estimated by assuming that the SRC beam has a stiffness given as the sum of the stiffness of the reinforced concrete component (considering the effect of creep) and the stiffness of the steel component (without the effect of creep).

5. AMENDMENT OF SRC DESIGN PROVISIONS

The superposed strength method was found to lead inaccurate estimates for the strength of SRC members whose steel is 590MN/m^2 or larger in ultimate strength. The writers propose the following procedure for applying this method to estimate the strength of such SRC members. The strength of a SRC member is given as the superposed strength obtained by assuming that the concrete strength in compression is β (a value less than unity) times the nominal concrete strength (that used for SRC members with mild-steel), or the superposed strength obtained by assuming that the ultimate strength of steel in compression is limited to 390 MN/m^2, whichever is greater. Figure 10 shows an example of the results obtained by this amended procedure.

6. CONCLUSIONS

(1) For the flexural strength of a SRC member, the superposed strength method is applicable if steel does not exceed 590 MN/m^2 in ultimate strength. For the shear strength, the method provides an unsafe estimate when the ultimate strength of steel is 590 MN/m^2 or larger. Amendment of the superposed strength method was proposed so that it can be utilized for SRC members with steel having a higher ultimate strength.

(2) SRC members subjected to axial force and repeated shear, failed in either flexure or shear, are more ductile when steel has a higher ultimate strength.

(3) If a SRC member has a section whose cross sectional area of the steel component is reduced, ductility decreases particularly when the yield ratio is large. Reinforcement at such a section can improve ductility, making possible full recovery in ductility when the section is located within the span, but it is difficult to fully recover the ductility when the section is corped at a beam-to-column connection.

REFERENCES: [1] Wakabayashi, M., Japanese Standards for the Design of Composite Buildings, Proc. of Engineering Foundation Conference on Composite Construction in Steel and Concrete, Henniker, New Hampshire, June 7-12, 1987, pp.53-70.

ACKNOWLEDEMENTS: The writers are grateful for the support and assistances given by the Kozai Club, Japan, and those participated in this research project.

Table 1 Material Properties of Steel

Yield Ratio		0.7	0.8	0.9
Ultimate	390	47		
Strength	590		68	69
(MN/m^2)	780			89