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REINFORCED CONCRETE MEMBERS WITH REINFORCING BARS YIELDING IN STEEL SLEEVES

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SUMMARY

This paper studies the new reinforced concrete structural members which have steel sleeves covering longitudinal reinforcing bars of almost the same length as the depth of members at the hinge region (edge parts of members). In the area of about one forth of the length of steel sleeve, where is far apart from the fixed end of a member, the longitudinal steel bars are integrated with the steel sleeve by join mortal. In the other area, the longitudinal steel bars are free inside steel sleeves. The structural tests of seven reinforced concrete beams verified their excellent deformation capacity with minor damage.

INTRODUCTION

Except for such buildings as those of base isolation systems and masonry structures, buildings are structurally designed so that the members may yield and absorb the energy due to earthquakes.

As for reinforced concrete structures, it is highly recommended to design the beam yielding mechanism [1]. However, severe cracking and crushing of concrete, buckling of longitudinal reinforcing bars, and sometimes collapsing of buildings occur for reinforced concrete structures after yielding.

This study is aimed to develop the new reinforced concrete structural members which have excellent deformation capacity without any severe damage. In order to achieve this purpose, it is examined that longitudinal bars of the members are un-bonded at either edge part or anchor part of the members, so the members may be capable of deforming without any severe damage or deterioration in strength, and of absorbing great amount of energy.

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Such type of structures with un-bonded steel bars have been researched and developed for prestressed concrete structures in order mainly to avoid fracture of PC bars, since US-Japan prestressed concrete research (PRESSS) was launched [2],[3].

HINGE ISOLATED REINFORCED CONCRETE STRUCTURES

The ideal illustration of seismic performance of conventional reinforced concrete columns and targeted new ones is presented in Figure 1. As illustrated in the figure, conventional columns are suffered from severe damage at the hinge region in the case of a large deformation being forced by an earthquake. On the other hand, targeted new ones can absorb great energy without any severe damage or deterioration in strength.

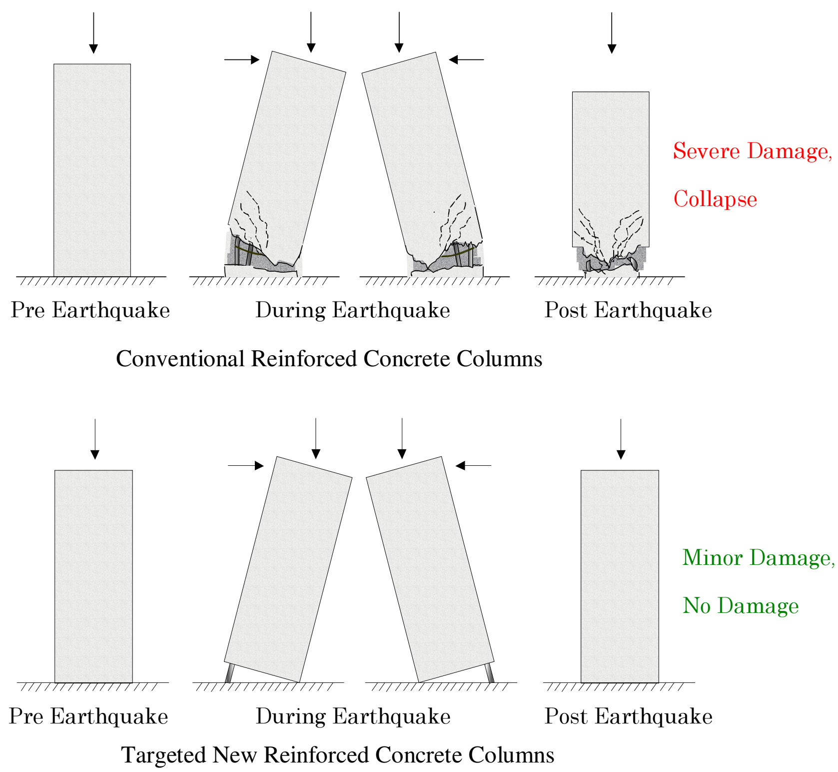


Fig.1 Illustration of Seismic Performance of Columns

Following two methods may be introduced to satisfy such targeted performance.

Method 1: Formation of yielding hinge in member

The longitudinal steel bars are un-bonded at the edge parts of members. However, a bond between longitudinal steel bars and concrete is a very important factor of resisting mechanism to shearing stress. And if longitudinal steel bars in the edge parts of members are un-bonded, there is no reinforcement to resist together with concrete to bending moment. It means that original structural performance of reinforced concrete members is lost. Therefore, the new system should consider a suitable counter measure to such conditions.

Method 2: Formation of yielding hinge in anchorage
In this method, the longitudinal steel bars of members are un-bonded and yield in the part of anchorage. This system may be applicable to the first-floor columns supported by deep foundation beams and the coupling beams of structural walls. The sufficient treatment to prevent from yielding of longitudinal steel bars in the other regions is necessary for this system.

HINGE SYSTEMS IN STEEL SLEEVEES

Figure 2 shows a hinge system in steel sleeve as an example of hinge isolation structural system. Figure 3 shows its deformation mechanism.

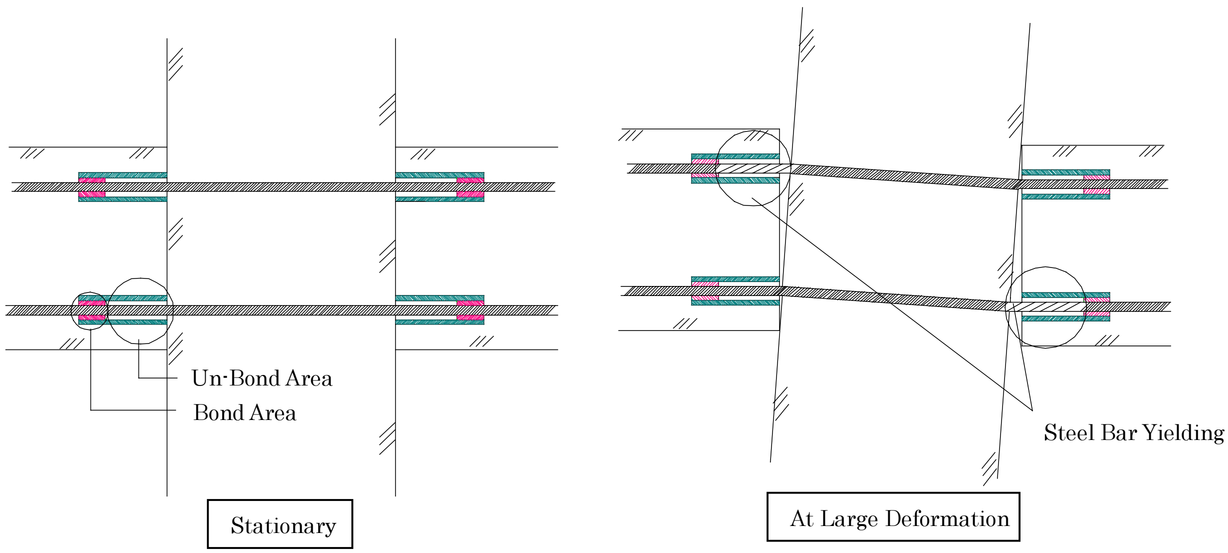


Fig.2 An Example of Hinge Isolation Structural System

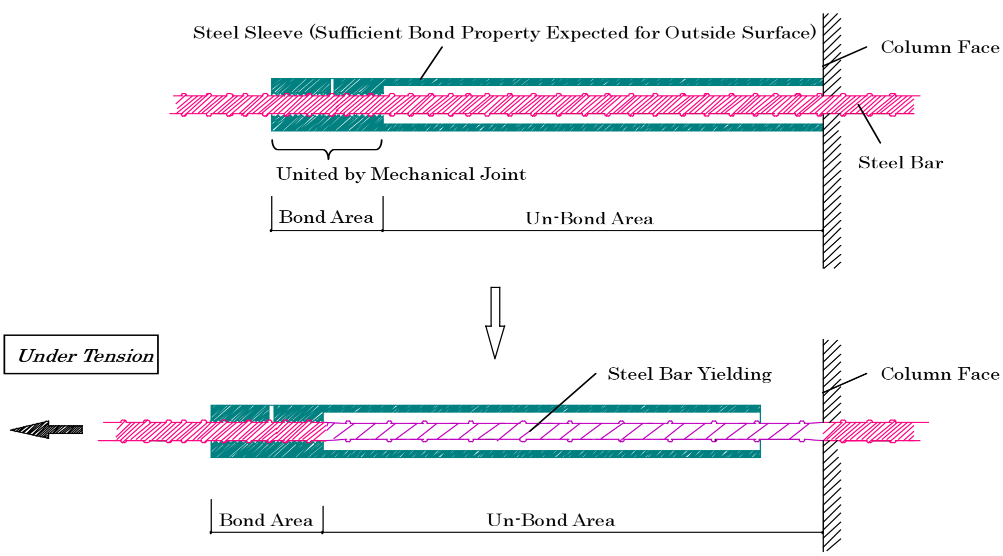


Fig.3 Deformation Mechanism

This system has steel sleeves covering longitudinal reinforcing bars of almost the same length as the depth of member, at the hinge regions (edge parts of members). In the area (Bond Area) of about one forth of the length of steel sleeve, where is opposite part of the fixed end of a member, the longitudinal steel bars are integrated with the steel sleeve by joint mortal. In other area (Un-Bond Area), the longitudinal steel bars are able to yield without any restriction of concrete, and never buckle because of the steel sleeves. Furthermore, the steel sleeve resists bending moment with concrete.

EXPERIMENT OF HISS REINFORCED CONCRETE BEAMS

Structural experiment of reinforced concrete beams of this system (Hinge Isolation Structural System, hereafter referred to "HISS") was conducted to investigate their seismic performance. The experiment focused on the merit of this structural system; the damage at the edge parts of members rarely occurs in this system. Specimens consist of beams with opening at the both edge parts of the beam. It has been difficult for conventional reinforced concrete members to have such openings because they significantly deteriorate in shear capacity after yielding of members.

Specimens and Loading

There are seven specimens. All specimens have the same dimensions of beam width(250mm), depth(350mm) and clear span(1400mm). Shear-span ratio is 2 and the design compressive strength of concrete (Fc) is 30 N/mm^2. Each opening 100mm in diameter is located at the middle of the beam. The distance between the center of the opening and the beam end is 120mm. Figure 4 shows reinforcement arrangement and Table 1 shows outline of the specimens. All specimens were designed to fail in flexure prior to shear failure.

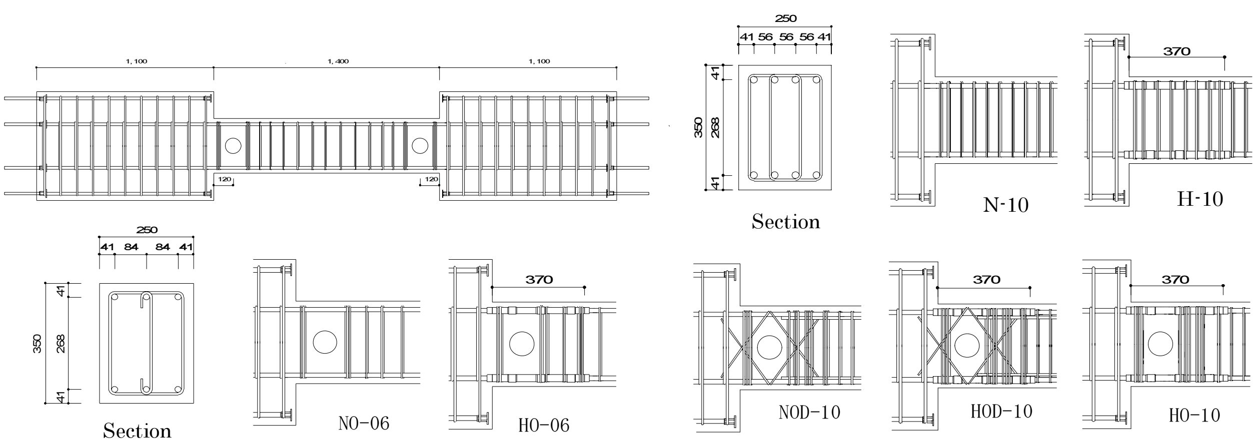


Fig.4 Specimens and Reinforcement Arrangement

The longitudinal steel bars of the specimens NO-06 and HO-06 are 3-D19(SD295)(three deformed bars with nominate yield stress of 295N/mm^2). Those of the specimens N-10, H-10, NOD-10 and HO-10 are 4-D19(SD345). Stirrups for openings of the specimens NO-06 and HO-06 are 3-D6(KSS 785: nominal yield stress of 785 N/mm^2), and those of the specimens N-10, H-10, NOD-10, HOD-10 and HO-10 are 4-D6(KSS785). Diagonal reinforcement for openings is 4-D6(KSS785). Stirrups of the specimens NO-06 and HO-06 are 3-D6 @90(SD295), and those of the specimens NO-10, H-10, NOD-10, HOD-10 and HO-10 are 4-D6 @50(SD295).

Table.1 Specimens

Specimens	NO-06	HO-06	N-10	H-10	NOD-10	HOD-10	HO-10
τ level	0.06Fc		0.10Fc				
Longi Steel Bars	3-D19 (SD295)		4-D19 (SD345)				
Stirrup	3-D6@90 (SD295)		4-D6@50 (SD295)				
Steel Sleeve	None	Use	None	Use	None	Use	Use
Opening Size	D/3.5		None		D/3.5		
Opening	120(mm) from Beam-end		-		120(mm) from Beam-end		
Stirrup for Opening	6-D6 (KSS785)		-		8-D6 (KSS785)		
Diagonal Reinforcement	None		-		4-D6(KSS785)		None
Flexural Strength (2M/L)	86200(kN·mm)		128000(kN·mm)				
	123(kN)		182(kN)				
Shear Strength	134(kN), No Opening 133(kN), Opening		214(kN), No Opening -		214(kN), No Opening 208(kN), Opening		
Ratio of Shear Strength to Flexure Strength	1.09 (No Opening) 1.08 (Opening)		1.17 (No Opening) -		1.17 (No Opening) 1.14 (Opening)		
Bond Stress	3.16(N/mm^2)		3.76(N/mm^2)				
Bond Strength	3.40(N/mm^2)		4.25(N/mm^2)				
Common Factor							
Fc	30 (N/mm^2)						
Shear Span Ratio	2.0						
Span	1400 (mm)						
Dimentions	250(mm) × 350(mm)						

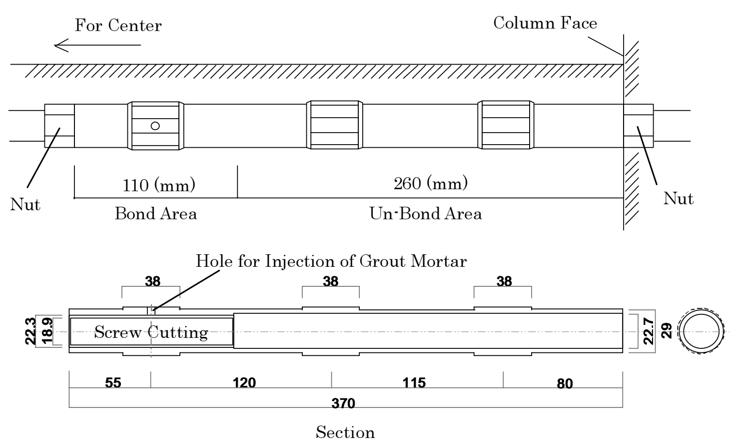


Fig.5 Detailed Section of Steel Sleeve

Tables 2 and 3 show the test results for the material property of steel bars and concrete. Figure 5 shows detailed section of steel sleeve. The length of the steel sleeves is 370 mm. The length of Un-Bond Area is 260 mm and that of Bond Area is 100 mm. A steel sleeve has three projections on its surface in order to have good bond property. The outer diameter of steel sleeve is 29mm, and the part with projection is 31mm. The inside diameter of steel sleeve is 22.7 mm for Un-Bond Area, and 18.9 mm, 22.3 mm for Bond Area. The longitudinal steel bars are screwed into the Bond Area, and then the joint mortal is poured into the Bond Area. The nuts at the both ends of steel sleeve were placed only for construction.

Table.2 Material Property of Steel Bar

Steel Bar	Tensile Strength (N/mm^2)	Yield Strength (N/mm^2)	Elastic Modulus ($\times 10^5 N/mm^2$)	Strain at Yielding (μ)	Strain at Fracture (%)
D19(SD295)	528	348	1.72	2020	21.2
D19(SD345)	583	380	1.77	2340	18.4
D6(SD295)	514	350	1.70	2100	16
D6(KSS785)	1170	900	1.71	5230	1.83
D10(KSS785)	1050	855	1.69	5100	10.1

Table.3 Material Property of Concrete

Specimens	Curing Method	Compression Strength (N/mm^2)	Elastic Modulus ($\times 10^4 N/mm^2$)	Spilling Strength (N/mm^2)
NO-06,HO-06 N-10,H-10 H0-10	Air Dried	32.9	2.98	3.01
NOD-10 HOD-10	Air Dried	30.4	3.02	3.11

Double curvature loading system was applied to the specimens. As for standard loading cycles, reversed cyclic loading were twice on the target drift angles of R=1/400, 1/200, 1/100, 1/50 and 1/30, and then one reversed cyclic loading on the target drift angle of R=1/25, and finally the target drift angle of R=1/20 was monolithically loaded.

Experimental Results

Outline of test results

Figure 6 shows relationships between shear force and drift angle of all specimens, and the comparison between the specimens N-10 and Ho-10. At the loading stage (Q=117kN, R=1/95) of loading path to R=1/50, the specimen NO-06 deteriorated in strength and failed in shear, contrarily, the HISS specimen HO-06 didn't deteriorate in strength although it deformed until R reached to 1/20 (Q_{max}=139kN).

The specimen NOD-10, with diagonal reinforcement for opening failed in shear on the way (Q_{max}=190kN, AR=1/37) of loading path to R=1/33, hence, the HISS specimen HO-10 without diagonal reinforcement increased in strength up to R=1/25(Q_{max} =209 kN). The HISS specimen HOD with the diagonal reinforcement for opening increased in strength up to R=1/20 (Q_{max} =218kN), and showed excellent energy absorption.

The ultimate strength of the specimen N-10 was Q_{max}=224kN, and that of the HISS specimen H-10 was Q_{max} =219 kN. Both specimens did not fail up to the final loading state R=1/20, and the HISS specimen H-10 showed a slightly better hysteresis property. Almost the same hysteresis curves were observed for the specimen N-10 without openings and for the HISS specimen HO-10 with openings, although the ultimate strength, in the negative loading, of the HISS specimen Ho-10 was lower than that of the specimen N-10.

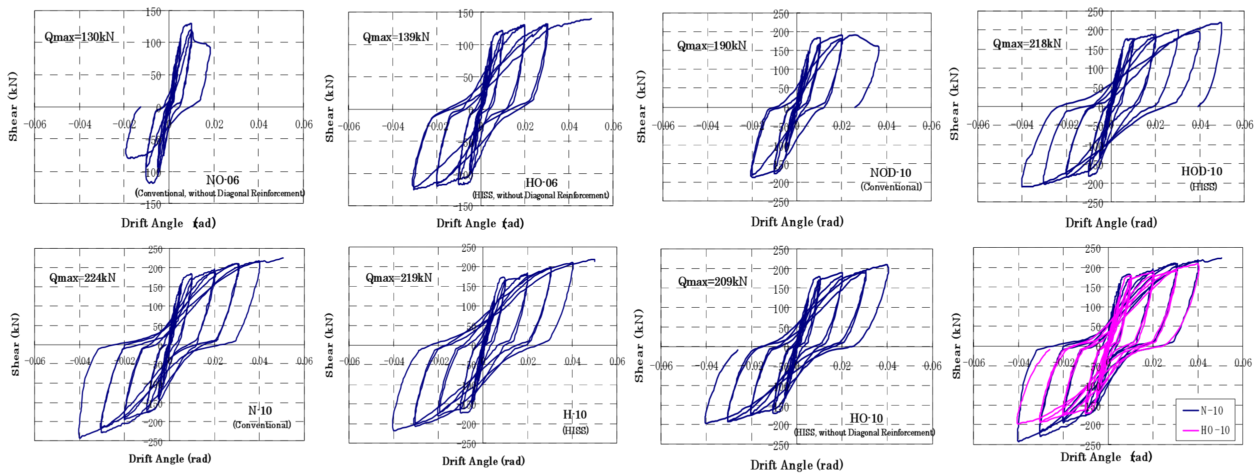


Fig.6 Relationships between Shear Force and Drift Angle of All Specimens

Initial stiffness and stiffness after flexural cracking

Figure 7 shows the relationship between the shear and the drift angle of the first loading cycle to examine the difference in initial stiffness between conventional members and the HISS. Deterioration in stiffness of the HISS specimen H-10 was relatively remarkable, compared to the specimen N-10. However, the stiffness in the negative loading was almost the same between the two specimens. The stiffness at yielding of the both specimens was almost the same.

Cracking pattern

Figure 8 shows the specimens after the test. The cracks around the openings occurred prior to other cracks for the specimens NO-06 and NOD-10. Then, these cracks were developed and linked to bond cracks occurred along the longitudinal steel bars, and finally caused the shear failure around the openings.

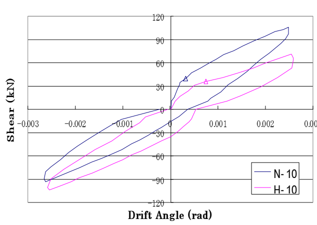


Fig.7 Initial Stiffness

NOD-10 (Conventional)

HO-10
(HISS, without Diagonal Reinforcement)

HOD-10 (HISS)

NO-06 (Conventional,
without Diagonal Reinforcement)

HO-06
(HISS, without Diagonal Reinforcement)

N-10 (Conventional)

H-10 (HISS)

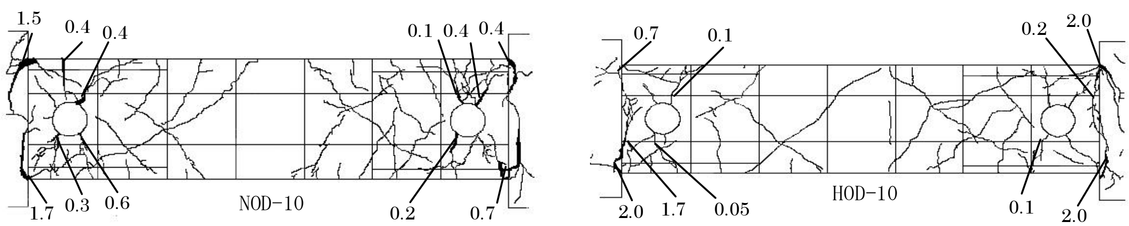
Fig.8 Specimens after Test

The crack width of shear crack in the hinge region of the HISS specimens HO-06, HO-10 and HOD-10 was significantly smaller than that of the conventional specimens, and the flexural broad crack appeared at the beam end for the HISS specimen.

A small number of cracks in the HISS specimen HO-10 without diagonal reinforcement for opening were observed in the hinge region. And in the HISS specimen HO-10 with diagonal reinforcement for opening, a smaller number of cracks were observed.

Many flexural shear cracks appeared in specimen N-10, hence, in the specimen H-10, broad flexural crack appeared at the beam end, and a few of other cracks were observed, whose width was very small.

Figure 9 shows cracks and their width at the drift angle of R=1/50 for NOD-10, HOD-10 and HO-10. Here, only the width of outstanding cracks in hinge regions is shown, and that of other cracks is not shown because it is very small. The maximum crack width around the openings at the drift angle of R=1/50 is 0.6 mm in the specimen NOD-10, 0.1mm in the specimen HOD-10,and 0.5 mm in the specimen HO-10, respectively.



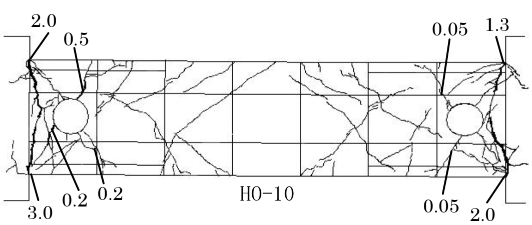


Fig.9 Cracks and Their Width at the Drift Angle of R=1/50

As mentioned above, in the HISS specimens, remarkably broad cracks were observed only at the beam end and very few and small cracks were observed in the hinge regions. Therefore, the repair work of the HISS members may be much easier than that of conventional members even if they suffer damage.

Discussion on Stress Transfer and Deformation Mechanisms

This chapter discusses the stress transfer mechanism and deformation mechanism of the HISS beams based on the test results.

Stress of steel sleeve

Here, the moments and stress in the hinge region of the HISS beam are discussed.

1) Bending moment of steel sleeve

Figure 10 shows the bending moments acting on the hinge region of the HISS beams. Here, the notation Ntt denotes tensile stress of tensile longitudinal steel bars, and the notations Ntc and Ncc denote compressive stresses of compressive longitudinal steel bars and concrete, respectively. If it is considered that the Ntt consists of Nttc and Ntcc, where Nttc and Ntc are balanced with Ntcc and Ncc, respectively, Nttc and Ntc are couple forces, and are considered as external bending moment acting on the anchorage section (A section in the Figure 10). As a result, at the hinge region the bending moments acting on the hinge region which exclude the un-bonded longitudinal steel bars is extraordinarily small compared to that in the hinge region of conventional beams, as shown in Figure 10. This was the major factor why cracks did not occur in the HISS specimens.

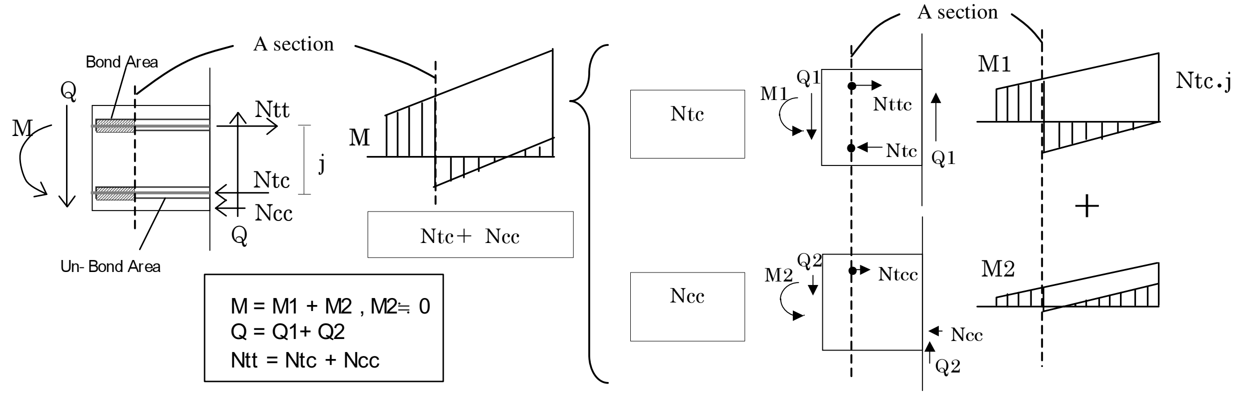


Fig.10 Bending Moments Acting on The Hinge Region

2) Relationships between strain of longitudinal steel bar and steel sleeve and drift angle
Figure 11 shows that the relationships between strain of longitudinal steel bar (gage No. D17) and steel sleeve (gage Nos. C10, C11 and C12) and drift angle. In the Bond Area, the steel sleeve elongates the same amount as longitudinal steel bar, but in the Un-bond Area, strain of steel sleeve is tensile when that of longitudinal steel bar is compressed and that of steel sleeves is compressive when the strain of longitudinal steel bar is tensile. It is also found that the strain (gage No. C12) of steel sleeve at the Un-bond Area is greater than strain (gage No. C11), as it is a just test result of the discussion mentioned above.

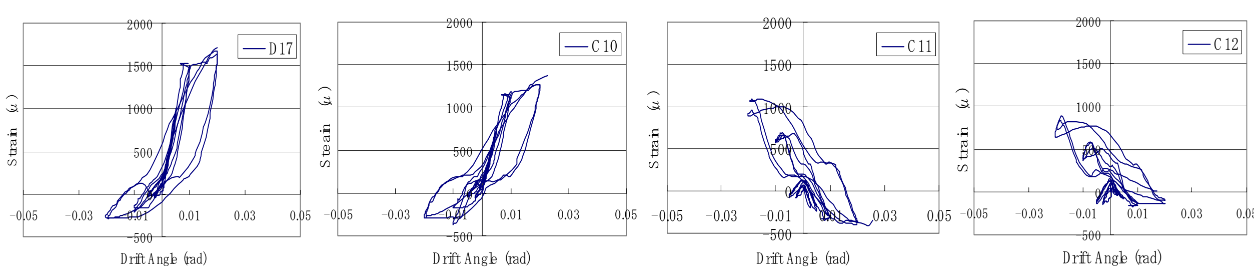


Fig.11 Relationships between Strain of Longitudinal Steel Bar and Steel Sleeve and Drift Angle【H-10】

Strain of stirrups
Figure 12 shows the strain of stirrups. Strain of stirrup (gage No. S13) at the Bond Area is almost the same for the conventional and HISS specimen.
The strains of stirrups (gage Nos. S14 and S15) of the HISS specimen are smaller than those of the conventional specimen, but their values are considered to be effective ones to resist shearing stress.

As a result, it may be concluded that the tress mechanism was formed even at the Un-bonded Area of the HISS specimens.

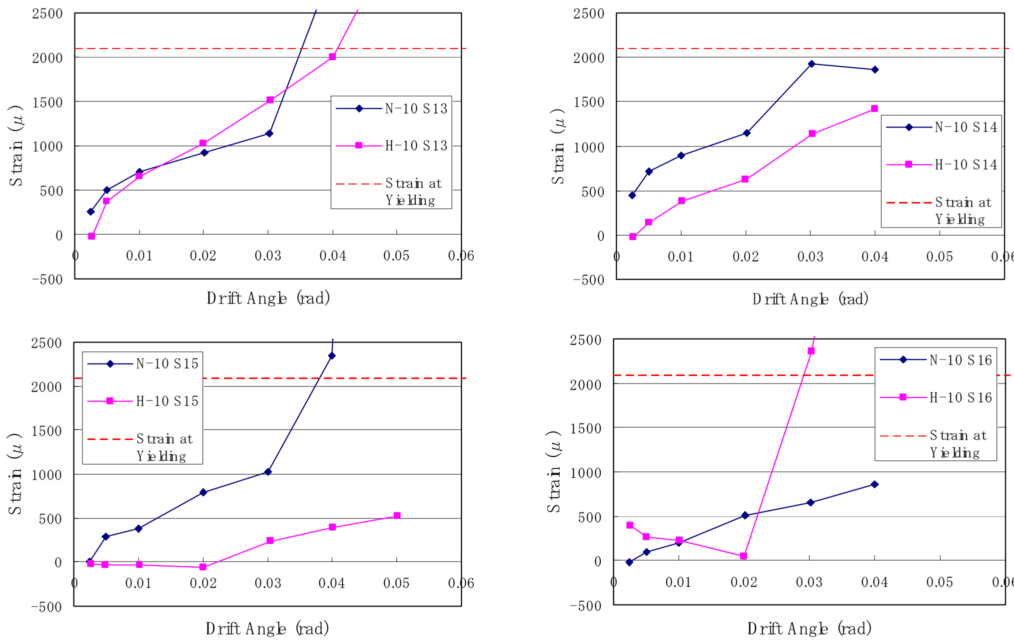


Fig.12 Strain of Stirrups

Deformation mechanism

Here, the deformation mechanism of the HISS member is discussed.

1) Curvature

Figure 13 shows the curvature distribution of the specimens NO-06, the specimens N-10, H-10 and the specimens NOD-10 and HOD-10. The curvature is widely outstanding in the hinge region in the conventional specimens, while it is concentrated at the member-end in the HISS specimens.

2) Shear deformation

Figure 14 shows the relationship between shear deformation and total deformation. According to the experiments, the shear deformation of the HISS specimens is remarkably less compared to that of the conventional specimens NO-06 and HO-06. The shear deformation of the HISS specimen HO-10 without the diagonal reinforcement for opening is less than that of the specimen NOD-10 with the diagonal reinforcement for opening. The shear deformation of the HISS specimen HOD-10 with the diagonal reinforcement for opening is much lesser.

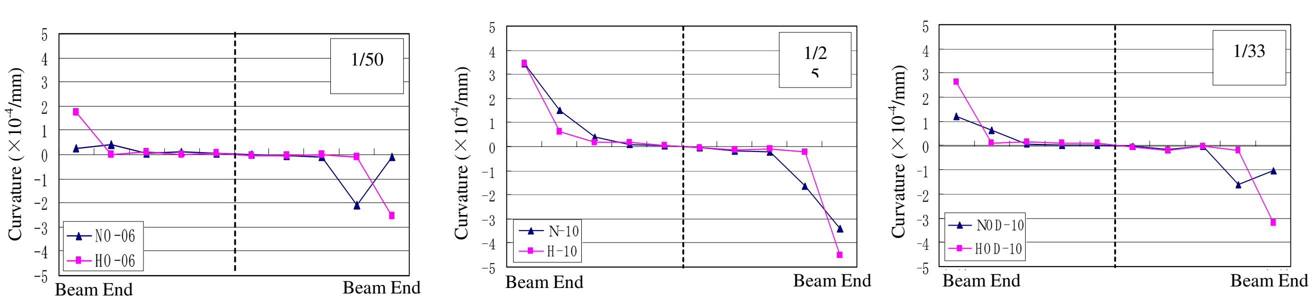


Fig.13 Curvature Distribution

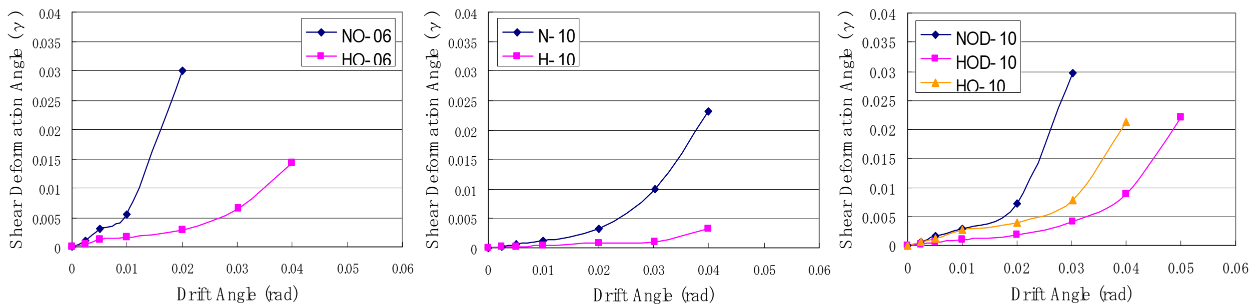


Fig.14 Relationship between Shear Deformation and Total Deformation

CONCLUSIONS

The following conclusions were drawn from this study.

1) The deformation capacity of the HISS beams with openings was much greater than that of the conventional ones.
2) The HISS beams with openings showed the same stable hysteresis property as the HISS beams without openings.
3) The cracks of the HISS beams were concentrated at the beam-end, and other cracks were few and their crack widths were small.
4) The bending moment acting on concrete at the hinge regions of the HISS beams was fairly small because the un-bonded longitudinal steel bars remarkably reduced the bending moments.
5) Effective truss mechanism was formed at the hinge regions of the HISS beams although the longitudinal steel bars were un-bonded in the regions.
6) Shear deformation of the HISS beams was extraordinarily small compared to that of the conventional beams.

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