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EXPERIMENTAL STUDY ON THE EFFECTS OF LOADING HISTORY ON THE DUCTILITY CAPACITY OF REINFORCED COMCRETE MEMBERS

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SUMMARY

The influence of loading history on the ductility capacity of reinforced concrete (RC) members and the mechanism of post-yield shear failure is discussed. Plural specimens designed identically were subjected to various loading histories including monotonic, uni-directional, bi-directional and constant width loadings. Results show that the ductility capacity depends on the loading history. This may be explained by the observation that the failure mechanism can vary due to loading history and this change in the mechanism affects the ductility capacity. Cross ties can control the swelling deformations of RC member and improve the ductility capacity in some cases, although these are found to be ineffective for specimens subjected to uni-directional cyclic loading.

INTRODUCTION

Reinforced concrete (RC) members subjected to cyclic loadings may fail in shear mode after flexural yielding of main reinforcement bars, even when the members are designed to fail in bending mode. There are some previous models to estimate shear strengths of RC members that take into account the post-yielding shear failure. In Japanese design codes for RC columns [1], the compressive strength of the concrete in the hinge zone is lowered by using an effective compressive strength based on the assumption that the compressive strength of the concrete deteriorates due to cracking. In Pujol's model [2], where the member shear strength is calculated based on the Mohr-Coulomb criterion, the lowering of member shear strength due to deformation is expressed by assuming that the term of adhesion in Coulomb's failure criterion deteriorates because of cracking.

Kinugasa [3] pointed out that the ductility capacity of a RC member failing in shear after flexural yielding is strongly affected by its loading history. The above mentioned models for estimating the shear strength, however, do not take into account the loading histories, although they include the effects of the strength deterioration due to the enlargement of deformation only.

It is important to clearly define the ductility capacity of RC members because recent design criteria of structures permit some level of plastic deformation for the members. For quantitative estimation of ductility capacities of RC members, the mechanism of the post-yield shear failure must be considered and

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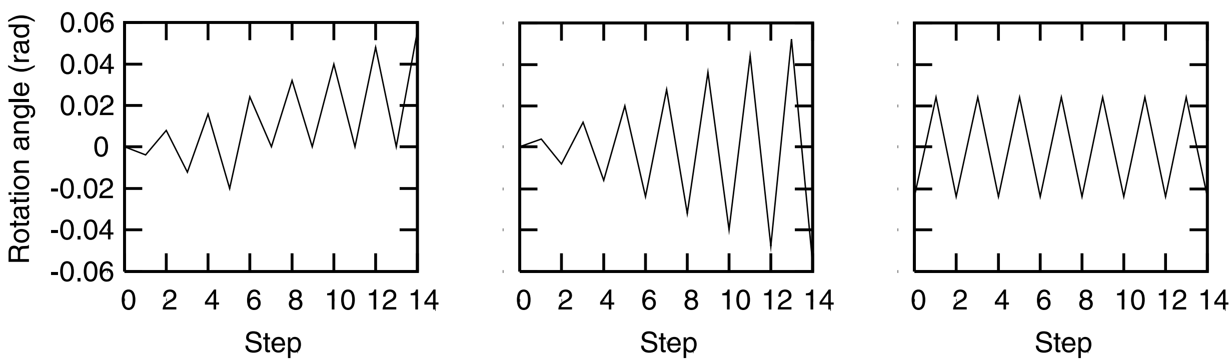
Table 1 Specimens

Name	Cross ties	Axial force ratio	Loading: Type	Loading: Width (rad)	Design strength (kN): Bending	Design strength (kN): Shear
AN1	X	0	Monotonic		95.06	174.4
AN2			Bi-dir.	4/1000 incremental		
AN3		0.062	Monotonic		117.6	
AN4			Uni-dir.	4/1000 incremental		
AN5			Bi-dir.	4/1000 incremental		
BN1		0.12	Monotonic		137.7	160.2
BN2			Uni-dir	3/1000 incremental		
BN3			Bi-dir.	3/1000 incremental		
BN4			Bi-dir.	17/1000 constant		
BN5			Bi-dir.	24/1000 constant		
BS1	O		Monotonic			166.4
BS2			Uni-dir.	3/1000 incremental		
BS3			Bi-dir.	3/1000 incremental		
BS4			Bi-dir.	6/1000 incremental		



(a) Uni-directional cyclic loading (b) Bi-directional cyclic loading (c) Constant width cyclic loading

Figure 1 Loading histories

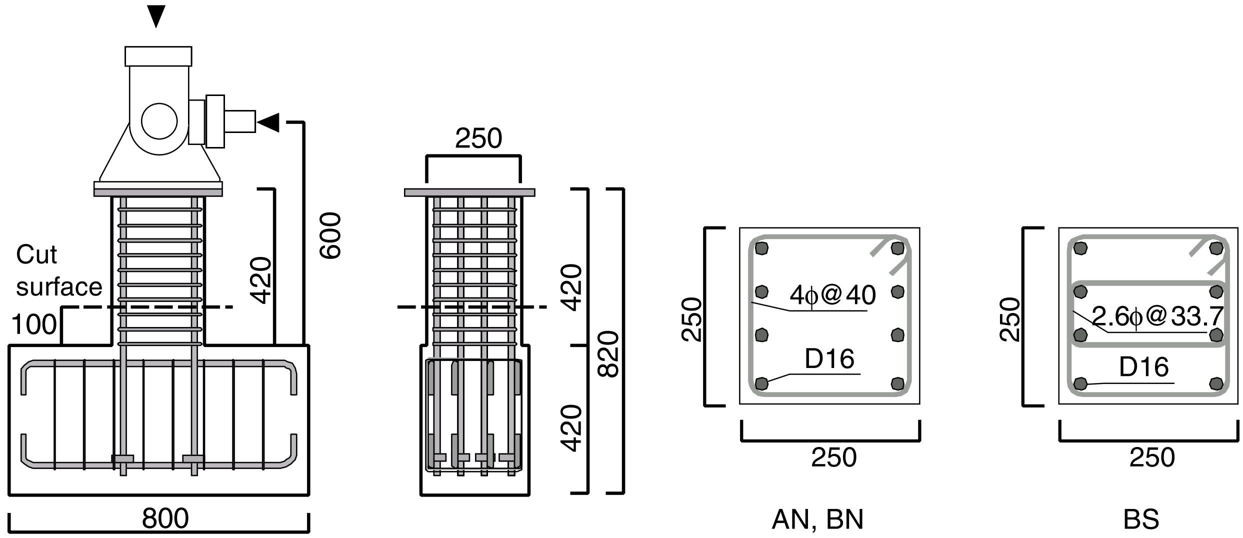
the effect of loading history should be included in the formulation. In this paper, experiments were conducted on RC specimens with the same design criteria under various loading histories in order to study the effects of cyclic loading history on the post-yield shear failure and member ductility.

EXPERIMENTS

Specimens

The properties of the specimens are shown in Table 1. There are three identically designed groups, namely AN series, BN series and BS series. The elevations and the hoop details are shown in Figure 2. the design of the AN and the BN series are almost identical, but the materials are slightly deferent. Cross ties are arranged for BS series, while the diameter and the spacing of the hoop reinforcement were designed so that the hoop reinforcement ratio (p_W=0.25%) are the same as that of the other series. The material properties are shown in Table 2 and Table 3.

The specimens of each group were subjected to various loading histories including monotonic pushover, uni-directional cyclic loading, bi-directional cyclic loading and constant width cyclic loading, as



(a) Elevations (b) Sections

Figure 2 Specimen details (Unit: mm)

Table 2 Material properties of steel bars (N/mm^2)

		Yield strength	Tensile strength	Young's modulus
A series	Main bar(D16)	360	460	1.94×10^5
	Reinforcement bar(4ϕ)	456	524	2.54×10^5
B series	Main bar(D16)	360	455	1.95×10^5
	Reinforcement bar(4ϕ)	531	577	1.98×10^5
	Reinforcement bar(2.6ϕ)	530	578	1.86×10^5

Table 3 Material properties of concrete (N/mm^2)

	Compressive strength	Tensile strength	Young's modulus
A series	31.6	2.69	2.33×10^4
B series	31.2	3.48	2.46×10^4

illustrated in Figure 1. Design strengths calculated based on the Japanese code are also shown in Table 1. Each specimen was designed so that the design shear strength is slightly larger than the bending strength in order to let it fail after flexural yielding.

Test setup

The specimens were subjected to shear loads with various histories, including monotonic loading, uni-directional incremental cyclic loading, bi-directional incremental cyclic loading and constant width cyclic loading, under constant or no axial force, using the test rig shown in Figure 3(a). For the uni-directional cyclic loading, the specimen was subjected to bi-directional cyclic loading until the main reinforcement bars yielded.

To investigate the damage accumulation, the average internal strains of the core concrete were measured by the instrumentations illustrated in Figure 3(b). Each specimen was loaded until the resisting shear force decreased to 80% of the maximum force. The overall deflection and the axial deformation were measured as the relative displacement of the loading point against the stub.

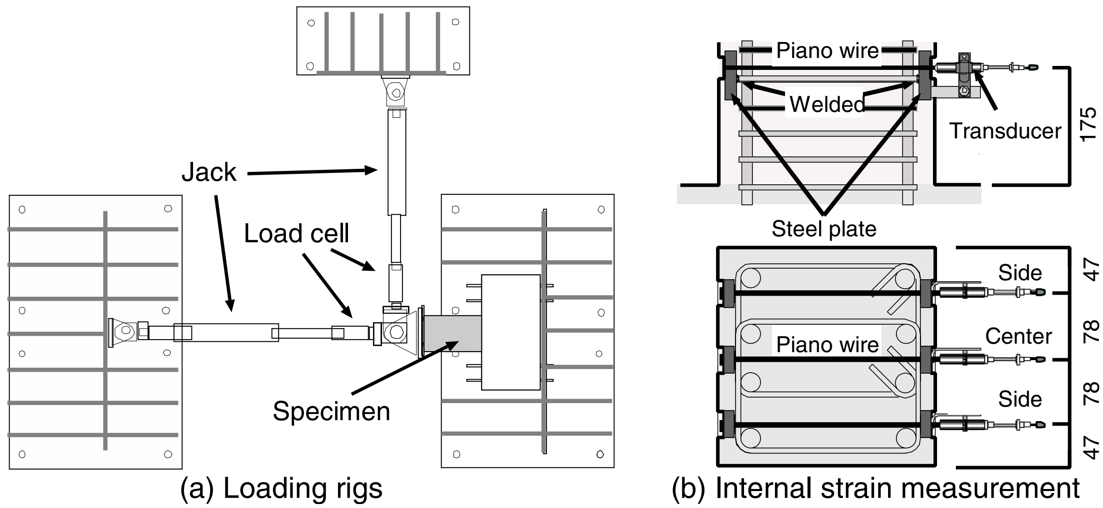


Figure 3 Test setup

TEST RESULTS AND DISCUSSIONS

Load-deflection relation

The lateral load-overall deflection relations of the specimens tested are shown in Figure 4. The contributions of the P-delta effect were eliminated from the lateral loads. Circles are drawn at the points where the strength deterioration started. All specimens failed in shear after flexural yielding.

The ductility capacity of the specimen under monotonic loading (AN1, BN1 and BS1) was the largest for each series. It is evident that the ductility capacity is strongly dependent on the loading history.

For the AN series, the deformation capacity of AN4, which was subjected to uni-directional cyclic loading, was smaller than that of AN5 under bi-directional loading, although the number of cycles for AN4 is less than that for AN5. On the other hand, this reversion is not seen for BN series, although the designs of the specimens for those series are very close.

For the specimens subjected to constant width cyclic loadings, the strength did not deteriorate after many cycles for BN4, which was loaded using a small width, while strength of BN5 under a large width of cyclic loading deteriorated after a few cycles. This result implies that for constant width cyclic loadings, a limit width seems to exist between the two loading widths used for the specimens wherein the strength deteriorates when exceeded. With regard to the BS series with cross ties, the strength deteriorated in fewer cycles for BS4 with a larger deformation increment for each cycle, than for BS3 with a smaller increment. This reversion of the number of cycles and the deformation capacity resembles the relation between AN4 and AN5.

Comparing the effect of cross ties in the BS series and BN series, the deformation capacities of BS1 and BS3 are larger than those of BN1 and BN3, respectively. On the other hand, the deformation capacity of BS2, which was subjected to uni-directional cyclic loading, is almost the same as that of BN2. It can therefore be concluded that cross ties cannot improve the deformation capacities of RC members under some kinds of loading history.

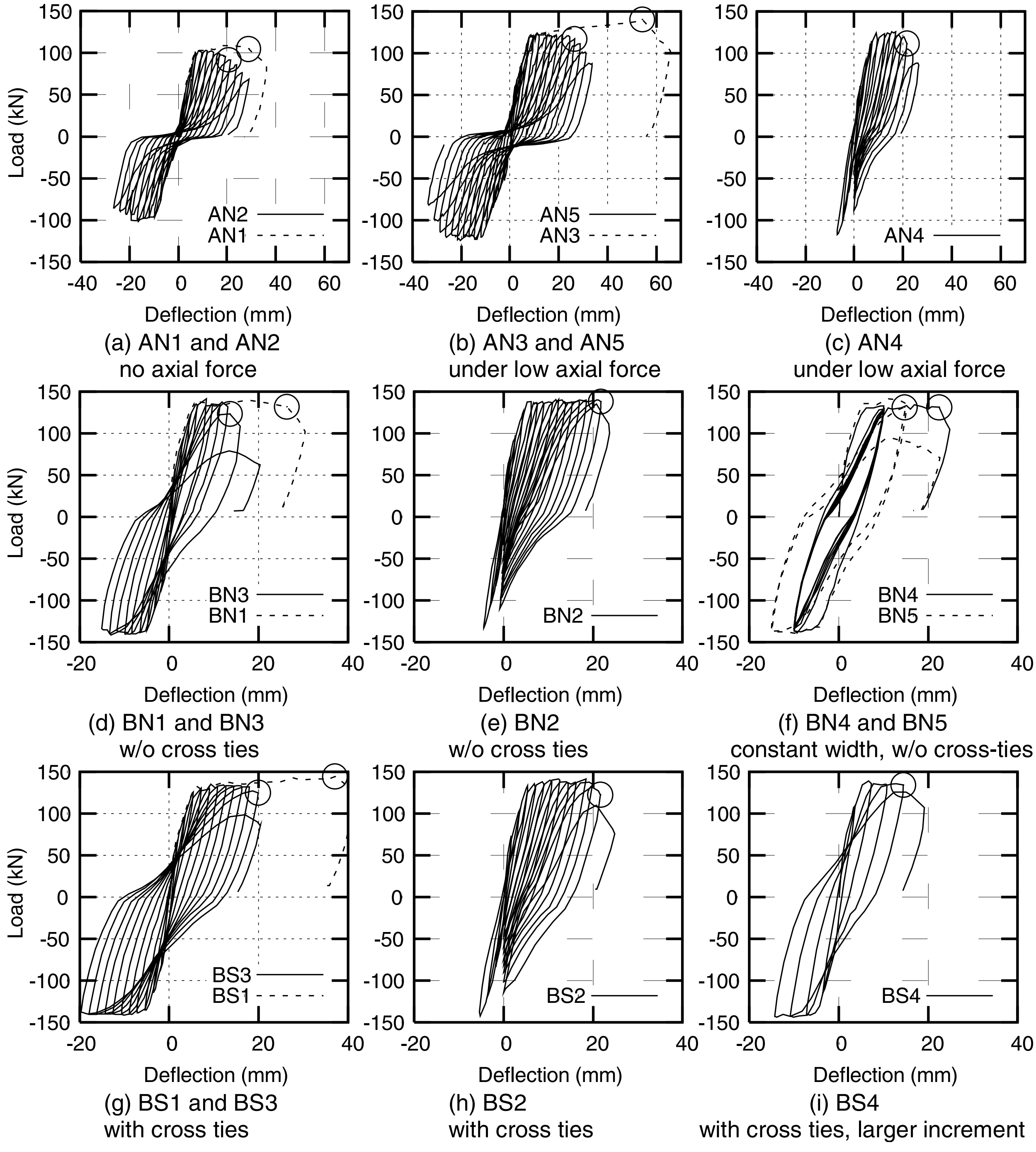


Figure 4 Load-deflection relations

Internal strain

The internal strain-overall deflection relations of the specimens tested are shown in Figure 5. In order to get the internal strain, the transverse deformations were measured by the instrumentations illustrated in Figure 3(b) and divided by the column's effective depths (212mm). Circles are drawn at the starting point of the strength deterioration. The solid lines denote the internal strains measured at the center of the sections while the dotted lines denote the averages of the strains at both sides.

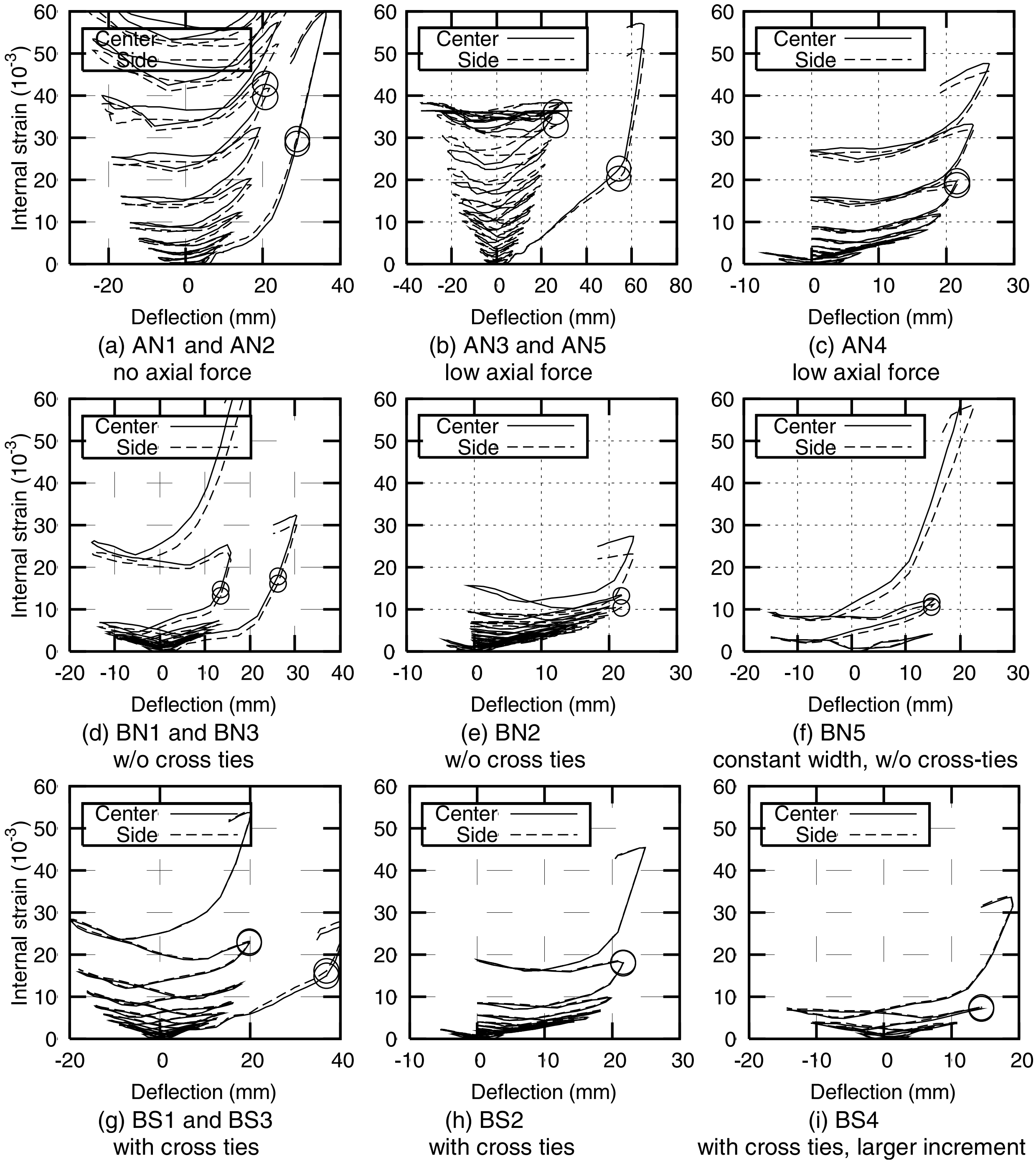
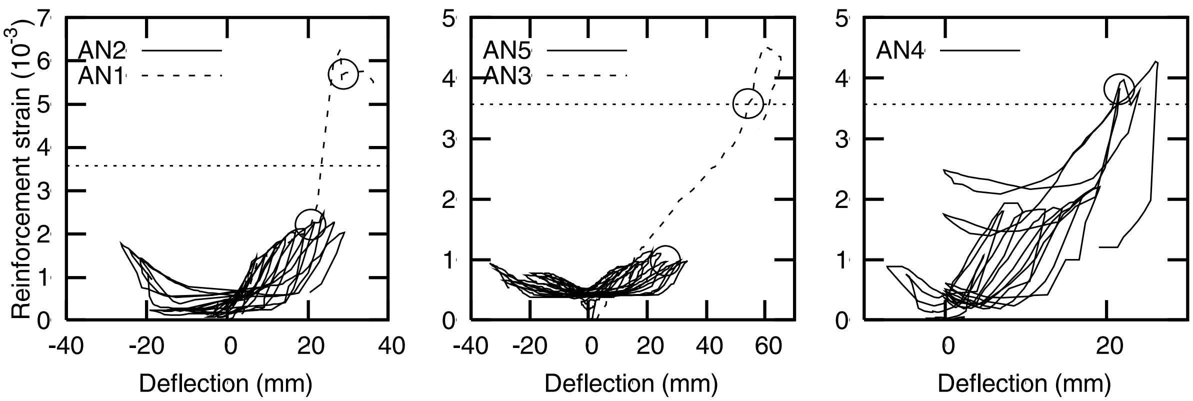


Figure 5 internal strain-deflection relations

With regard to the AN series, which are subjected to no or small axial forces, swelling deformation of the sections (measured as the difference between the "Center" and the "Side") are larger for AN2 and AN5 (subjected to bi-directional cyclic loadings) than for AN1, AN3 and AN4. In other words, the swelling deformation occurs more easily for members under bi-directional cyclic loadings compared to members under uni-directional cyclic or monotonic loadings. Figure 6 shows the strains of transverse reinforcement of AN series. The dotted lines denote the yielding strain of the steel. The transverse reinforcement bar of



(a) AN1 and AN2
no axial force

(b) AN3 and AN5
low axial force

(c) AN4
low axial force

Figure 6 Strains of transverse reinforcement bars

(a) Two dimensional deformation with yield of reinforcement bars

(b) Swelling deformation

Figure 7 Section deformation patterns

AN2 and AN5 (subjected to bi-directional cyclic loading) yielded near the strength deterioration, while those of the other specimens did not yield. Moreover, we cut the specimens at the level surface 10cm above the stub in order to observe the cross section. The cutting surface is illustrated in Figure 2(a). The crack patterns at the sections of AN4 and AN5 are shown in Figure 8. The crack patterns agree well with the observations of the internal strains. The cracks on the section of AN4 are fewer and thicker than those of AN5. The deformation localization may be one reason why AN4 failed at a smaller deformation than AN5. From these observations, we inferred the following mechanisms of the strength deteriorations,

- For uni-directional and monotonic loadings, many cracks did not develop and the crack patterns are simple. The section deformed simply as shown in Figure 6(a) and the deformation is localized in a few cracks. As a result, the transverse reinforcement bars yielded and the strength deteriorated in fewer cycles.
- For bi-directional loadings, many cracks opened in the specimen. The specimen deformed three-dimensionally and the section swelled as shown in Figure 7(b). As a result, the effect of reinforcement bars is reduced and the strength deteriorated without yielding of reinforcement bars.

In short, the failure mechanism can vary depending on the loading histories even if the members are designed identically, and this change in the mechanism strongly affects the deformation capacity.

For the BN series, subjected to larger axial forces, the internal strain started accumulating from small cycles only for BN3, which was subjected to bi-directional cyclic loading. The internal strains accumulated rapidly around the strength deterioration starting point, showing a strong relationship between the strength deterioration and the internal strain. The pattern of internal strain accumulation seems to be strongly influenced by axial forces, since the design of BN series is very close to AN series.

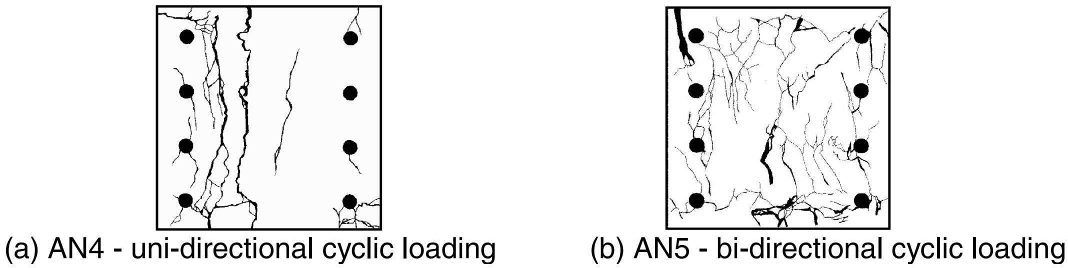


Figure 8 Crack patterns

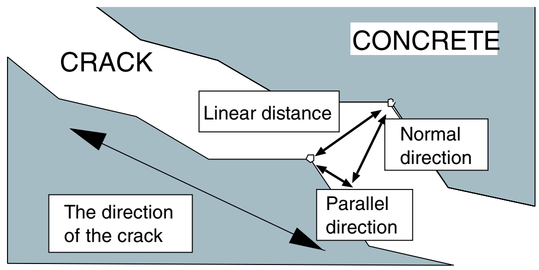


Figure 9 Definition of the components of crack width

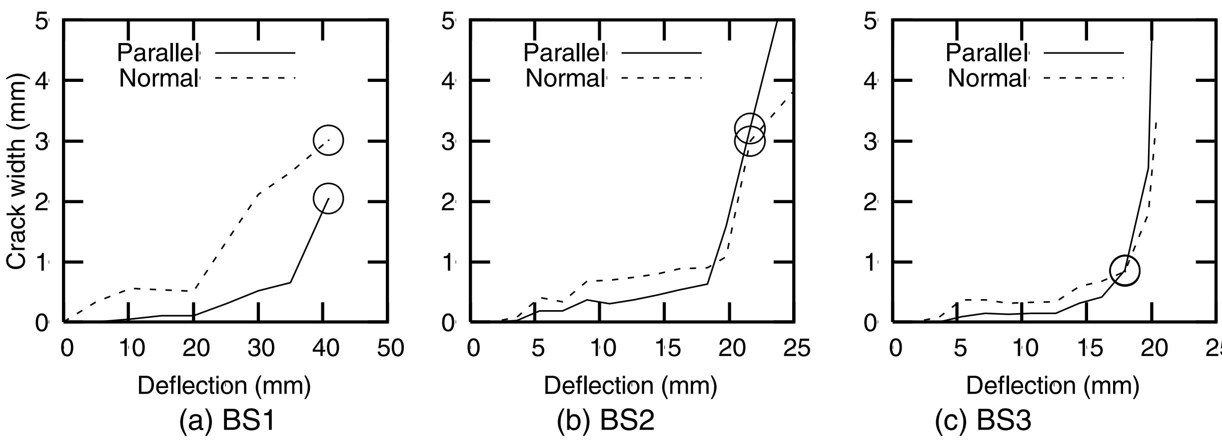


Figure 10 Widths of the thickest cracks

For the BS series with cross ties, the internal strain differences between the "Center" and "Side" are small for all the specimens. This means that the cross ties are effective in controlling the swelling deformation. The internal strains for BS3 are much smaller than those of BN3, which means the deformation capacity is improved by cross ties for the specimen subjected to bi-directional cyclic loading. However, the internal strains for BS2, which was subjected to uni-directional cyclic loading, did not decrease with the addition of cross ties because the internal strain for BN2 is also not very large. It is probable that the cross ties yielded in advance and the internal strain increased earlier for BS2 than for BN2. Therefore, cross ties arrangement may not be effective for the members subjected to some loading histories such as uni-directional loading history.

The internal strains for BN5 under a large cyclic loading width and for BS4 under the cyclic loading with the larger increment were smaller than those of the other specimens. We supposed that the crack patterns in these specimens are simpler than the other specimens subjected to more cycles for the same deformations, since these specimens were under smaller cycles. As a result, the deformations are localized and the reinforcement bars yielded earlier. In other words, deformations tend to be localized in a few thick cracks when the specimen is subjected to a small number of large deformation cyclic loadings. Therefore, number of cycles is not necessarily a proper index of damage for members that fail in post-yield shear failure.

Crack width

The width of the thickest crack of each specimen was observed for the specimens in the BS series. The crack widths were measured from photographs and resolved to the crack parallel and the crack normal components as shown in Figure 9. The surface cracks may have corresponded well to the inner cracks because the swelling deformations for the BS series are small. The crack width-overall deflection relations are shown in Figure 10. Circles are drawn at the points where the strength started deteriorating. In all cases, the crack parallel component increases sharply when the strength deteriorates although a clear relationship between strength deterioration and absolute value of crack width cannot be observed.

CONCLUSIONS

Experiments were conducted to investigate the effects of cyclic loadings on failure mechanisms and ductility capacities of members that fail after flexural yielding. Plural specimens designed identically were tested and the following results were drawn for members which fail in post-yield shear failure.

- The ductility capacity depends on the loading history. The failure mechanism can vary depending on the loading history and this change in failure mechanism strongly affects the ductility capacity.
- Cross ties can control the swelling deformation of sections without the need of increasing the steel amount and can improve the member ductility capacity in some cases. However, cross ties are not so effective on improving the ductility capacity for members in which many cracks do not open and swelling deformations hardly occur, such as in the members subjected to uni-directional cyclic loadings.
- When a member is subjected to cyclic loading with a large deformation increment, the crack pattern is simpler than that of a member loaded with a small deformation increment and the deformations concentrate in a few cracks. As a result, the specimen subjected to large increment cyclic loading may fail in fewer cycles than the specimens under small increment cyclic loadings. Therefore, the number of cycles is not necessarily a proper index of damage for members that fail in post-yield shear failure.
- The thickest crack slips suddenly along the crack when the strength deteriorates. This slippage of crack surface predominates the shear failure after flexural yielding of reinforced concrete columns.

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