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Elasto-plastic behavior of one-twentieth scale RC frame

Hiroyasu Sakata
Aichi Sangyo University, Japan

Akira Wada
Tokyo Institute of Technology, Japan

ABSTRACT This paper describes the structural behavior of the reinforced concrete (RC) frames based on the experiments on the one-twentieth scale models and also includes the analytical investigation. Focusing on the influence of the beam elongation, the experimental program consists of monotonic and cyclic loading tests on the four-story reinforced concrete frames with three spans. The structural behavior of the frames was also analyzed by the finite segment method.

As conclusions obtained from the experiments and analyses, (1) the lateral load vs. displacement relationship for each column in the frames was not identical due to the axial elongation of bending yield beams, (2) the lateral loads for all the frames was increased due to the axial restriction in beams caused by the lateral stiffness of columns, (3) the analysis results showed a good agreement with the experimental results.

1 INTRODUCTION

Reinforced concrete beams and columns forming up a structural frame exert influence on each other during loading and behave physically as one structural body. Thus, whenever analysis of the mechanical behavior of the reinforced concrete frame is concerned, experiment carried out on the frame as a whole system makes more sense than just experimenting on the individual member.

A loading test of a statically indeterminate reinforced concrete beam-to-column connection subassemblies was carried out by Zerbe and Durrani (1988), who pointed out that compressive force was developed in a beam which subsequently increased its flexural strength. Focusing on the restraint of the beam elongation, the author and his colleagues studied the behavior of the reinforced concrete beam subjected to the restraint of axial deformation (Kokusho, Hayashi, Wada and Sakata 1988). Sakata and Wada also studied the structural behavior of the reinforced concrete frame under monotonic loading and reported about the influence of the beam elongation (1991). Qi and Pantazopoulou (1991) investigated the experimental response of a single-story, indeterminate reinforced concrete frame and pointed out that the columns of the structure reacted to the lateral movement necessary to accommodate the increasing beam elongation.

In order to clarify the influence of the axial elongation of beams, horizontal loading experiments and analyses of a four-story three-span reinforced concrete plane frames were carried out. In this paper, the axial elongation of beams, the axial strain developed in the beams, the horizontal strength of the frame, the behavior of collapse mechanism, and etc. will be discussed.

2 METHODS OF EXPERIMENTS

2.1 Specimens

With reference to a certain reinforced concrete building with a pure rigid frame, a 1/20 scale plane frame was envisaged representing the lower portion of the building, and a total of two specimens; four-story, three-span specimen for monotonic loading test (FR3) and for cyclic loading test (FR3C) were manufactured. Each specimen represents the portion up to the intermediate height of the columns on the fifth floor erected on the fourth story of the specimen. The cross section of the members is shown in Fig.1. The dimension of specimen is shown in Fig.2. For the purpose of later explanation, the columns are marked to show A, B, C and D in order from the left to the right.

In lieu of concrete, the mortar with cement and standard sand proportioned at mixing ratio 1:2.5, which was mixed with water at a water-cement ratio of 75%, was used. D3 deformed reinforcement (Murayama et

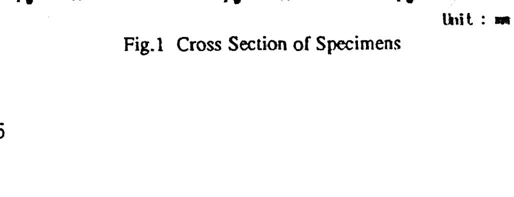


Fig.1 Cross Section of Specimens

al. 1982) used as main reinforcement was assembled with spiral hoops and stirrups manufactured from a 1.6mm diameter annealed wire.

2.2 Loading apparatus

The loading apparatus and the method of loading are shown in Fig.3, Fig.4 and Fig.5.

<Axial force of column> : Fig.4 shows the method of introducing the axial force of column, (N). The plate attached to the top of the column of each specimen was connected to the spring located in the spring case underneath the reaction frame, by means of a round steel bar with pin-shaped ends. By tightening the nut underneath the spring, the vertical force of 13.7kN per column was caused to act as a fixed load.

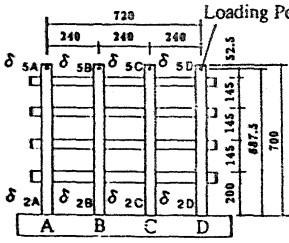
<Horizontal force> : As shown in Fig.5, each mini oil jack connected with one unit of hydraulic pump was installed downwards on the loading frame, so that the force could be transmitted from the mini oil jack to the loading plate and then to the loading frame, so that the force could be transmitted from the mini oil jack to the loading plate and then to the loading points. The loading plate had a needle bearing installed by the rotary shafts, so that the loading plate could be smoothly rotated. However, in order that the horizontal force acting on the columns at both ends be half that on other columns, the loading plate used was one in which the horizontal distance between the rotary shaft and the mini oil jack was half that between the others. The loading frame also serves as a means of preventing the specimen from out-of-plane buckling.

2.3 Mechanical properties of materials

Table1 shows the mechanical properties of the D3 deformed reinforcement, the 1.6mm diameter annealed wire, and the mortar which were used.

2.4 Loading path

The average horizontal displacement of the joint between the end columns and the end beams on the fifth floor was divided by the height (615mm) from the first-floor column base, and the value thus obtained was used as the whole average angle of rotation. Then monotonic loading was applied leftwards to the specimens FR3 until the whole average angle of rotation finally became 1/20 or more. Fig.6 shows the loading path of FR3C.



FR3 : Monotonic Loading
FR3C : Cyclic Loading

Fig.2 Specimen

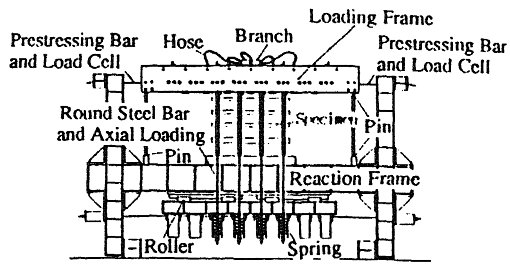


Fig.3 Loading Apparatus

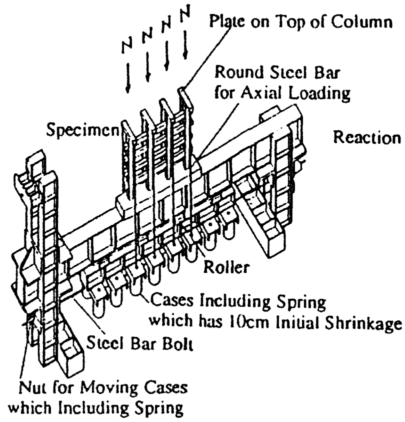


Fig.4 Loading Apparatus : Axial Loading

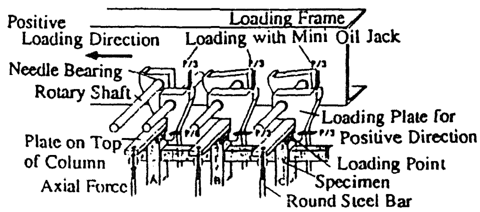


Fig.5 Inside of Loading Frame

Table1 Physical Properties of Materials

[Reinforcing Bar]

	Sectional Area (cm^2)	Yield Strength (MPa)	Tensile Strength (MPa)	Elongation (%)
D3	0.0731	317.3	440.9	40.7
1.6 ϕ	0.0201	253.7	383.8	—

[Mortar (FR3)]

			Exp.
Material Age (Day)	7	28	48
Compressive Strength (MPa)	21.5	32.2	42.1
Strain at Compressive Strength ($\times 10^{-6}$)	—	—	3711
Young's Mondulus (MPa)	—	—	22164
Tensile Strength (MPa)	1.8	2.4	3.2

[Mortar (FR3C)]

			Exp.
Material Age (Day)	7	28	43
Compressive Strength (MPa)	17.4	35.2	37.5
Strain at Compressive Strength ($\times 10^{-6}$)	—	—	3002
Young's Modulus (MPa)	—	—	253[illegible]
Tensile Strength (MPa)	—	1.7	1.[illegible]

3 RESULTS OF EXPERIMENTS AND DISCUSSIONS

3.1 Relationship between horizontal force and horizontal displacement

Fig.7 shows the relationships of monotonic loading (FR3) and cyclic loading (FR3C) between horizontal force and horizontal displacement. A monotonic loading experiment clarified that the horizontal displacements in the positions of the joints were not uniform. This phenomenon was more noticeable in a cyclic loading experiment. At the whole average angle of rotation 1/20, the difference between the horizontal displacements in the second floor beam-column joints at both ends (columns A and D) was 4.7mm in monotonic loading, whereas it was 5.5mm in cyclic loading. 'Simple analysis' in this figure shows the estimated horizontal resistance force of the specimens, which were obtained on the assumption that no axial force is developed in the beams of a collapse mechanism with a yield hinge assumed at the beam ends and first column bases. In either monotonic loading or cyclic loading, the resultant horizontal strength was greater than 'Simple analysis', for the principal reason that the axial elongation of the beams was restrained by the columns, hence increasing the flexural strengths of the beams. In cyclic loading, the horizontal displacement of the column A easily occurred in the positive direction (PO in Fig.7), whereas that of the column D easily occurred in the negative direction (NE in Fig.7). This phenomenon was noticeable, particularly in the horizontal displacement in the column-beam joints on the second floor.

3.2 Relationship between horizontal force and axial elongation of Beam

Fig.8 shows the relationship between horizontal force and the axial elongation of the second floor beam during cyclic loading. From the figure, it is evident that the elongation of a beam increases on every cyclic loading, and thereby plastic strain builds up. Ultimately, the second floor A-B beam, 2.35mm, B-C, 1.76mm, C-D, 1.92mm. Representing these values by the ratio of elongation to the inside length of beam, they are 1.21%, 0.90% and 0.99%. Fig.9 shows the axial elongations of the second floor beams in monotonic loading and cyclic loading when the whole average angle of rotation was 1/20. The elongations of beams in monotonic loading are greater in the order of beam C-D<B-C<A-B, whereas in cyclic loading the elongation of beam C-D is greater than that of beam B-C. This was because the cyclic loading caused the columns at both ends (columns A and D) to move outward, more than the columns B and C.

3.3 Axial strain of beam

Fig.10 shows the distribution of axial strains in the beams with the whole average angle of rotation 1/20. On the second floor, compressive strain was acting in all beams both in monotonic loading and cyclic loading. Although these compressive strains were in nearly the same order, they were greater in cyclic loading as a whole than in monotonic loading.

3.4 State of deformation

Fig.11 shows the state of deformation with the whole average angle of rotation 1/20, and Photo 1 presents the ultimate state of deformation. While in leftward loading, column D was largely bent in the form of '>', column A indicated a nearly straight deformation mode in both cases. In contrast with this ,while in rightward loading, column A was largely bent in the form of '<', column D

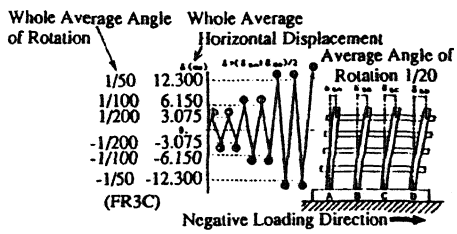


Fig.6 Loading Path for Cyclic Loading

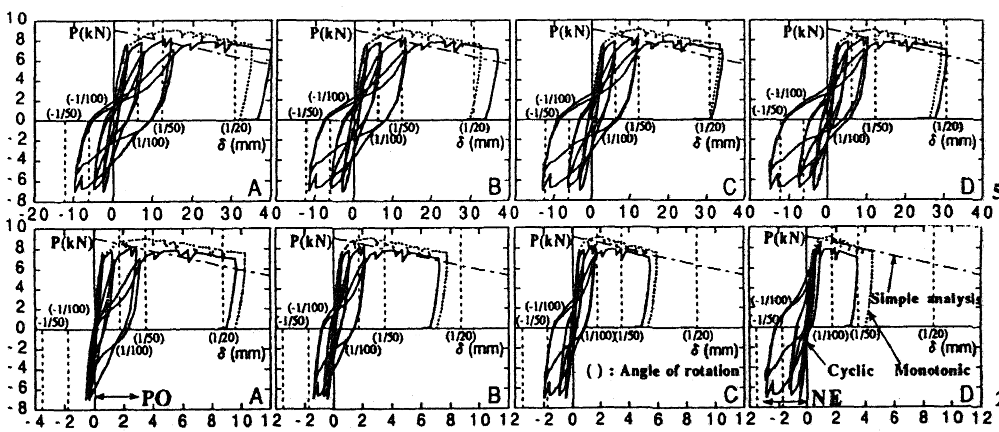


Fig.7 Horizontal Force - Horizontal Displacement Relationships

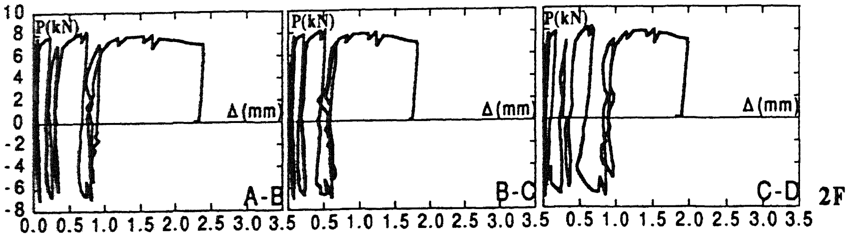


Fig.8 Horizontal Force - Axial Elongation of Second Floor Beam Relationships

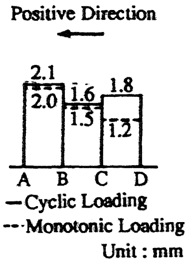


Fig.9 Axial Elongation of 2F Beam at Whole Average Angle of Rotation 1/20

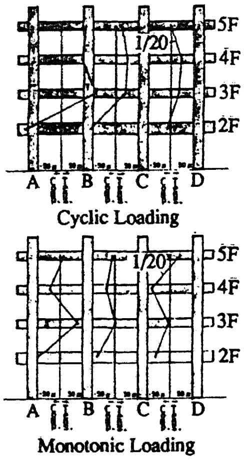


Fig.10 Axial Strain of Beam

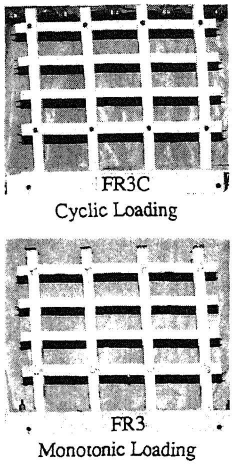


Photo1 State of Ultimate Deformation

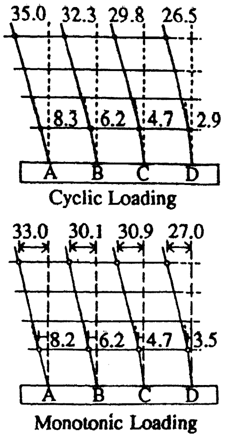


Fig.11 State of Deformation

indicated a nearly straight mode. This accounts for the fact that on the second floor beam C-D is more easily elongated than beam B-C during cyclic loading.

4 ANALYSIS METHOD AND ANALYSIS MODEL

By the implementation of the elasto-plastic analysis method of reinforced concrete frame taking into consideration shear deformation of beam-column joints and bond-slip using finite segment method, analyses of the present experiments were carried out. As the details of the elasto-plastic analysis method are given in Reference (Kokusho, Wada and Sakata 1988), explanation of the analysis method is omitted.

4.1 Analysis model

Fig.12 shows the model for the FR3 and the FR3C used in analyses. Each of the columns and beams between the panels was divided into 20 elements in the direction of its axis, the columns on the fifth floor were divided into 10 elements, and the cantilever beams projecting on the left and the right were divided into 5 elements.

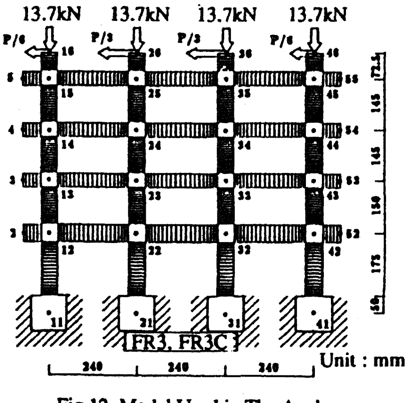


Fig.12 Model Used in The Analyses

4.2 Mechanical properties of materials used in the analyses

Table2 shows the constants used in the analyses in correspondence to the relationship between bond stress and slip (Fig.13), between stress and strain of concrete (Fig.14), between stress and strain of reinforcing bar

(Fig.15), and between stress and strain of concrete panel (Fig.16). The values obtained through material tests were applied as the values of the compressive strength of concrete, the yield stress of the reinforcement, etc., and the values involved in the bond slip of the reinforcement were modeled (Fig.13) with reference to the results of bond tests conducted by Murayama, et al.(1982).

5 RESULTS OF ANALYSIS AND DISCUSSIONS

Elasto-plastic analysis of specimens were carried out using the analysis method given in Section 4. The analytical results of FR3C will be only shown below.

5.1 Relationship between horizontal force and horizontal displacement

Fig.17 shows the relationship between horizontal force and horizontal displacement. The bold solid line represents the analysis results and the narrow solid line represents the experimental results. The analytical results indicates a spindle shape as a whole, and a reverse "S" shape which was seen in the experimental results appeared in some areas with small deformation, but did not appear in those with large deformation. This would be due to the effect of the shape of the hysteresis model used in the present analysis method as well as the consideration of only the flexural cracking developed perpendicular to the axis of a member. Both the analysis and the experimental values indicate a reasonable correspondence in strengths, and greater strengths than 'Simple analysis'. Also in the analysis, column A was easily deformed in the positive direction : leftward while column D like wise in the negative direction : rightward, and this phenomenon was noticeable in the horizontal displacement in the beam column joints on the second floor, as in the case of the experiment.

5.2 Relationship between horizontal force and axial elongation of a beam

Fig.18 shows the relationship between horizontal force and the axial elongation of a beam. In general, the analysis values are smaller than the experimental values. This would be because the experiment covered two rounds of loading for each loop, whereas the analysis covered one round. In the analysis also, it is evident that every cyclic loading caused the further elongation of a beam.

5.3 Relationship between horizontal force and shearing force in columns on the first floor

Fig.19 shows the relationship between horizontal force and shearing force in the columns on the first floor. The shearing force shared by the columns was not uniform because of the effect of axial elongation of the beams on the second floor, particularly a large difference seen between columns A and D. With loading applied in a positive direction, the shearing force in the column D was small, whereas that in the column A was small when loading in the negative direction.

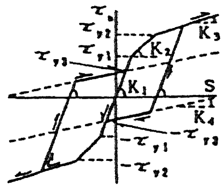


Fig.13 Bond Stress - Slip Relationship

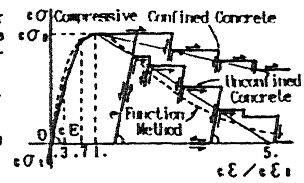


Fig.14 Stress - Strain Relationship of Concrete

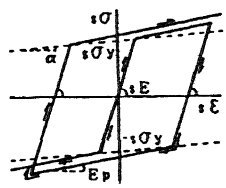


Fig.15 Stress - Strain Relationship of Rebar

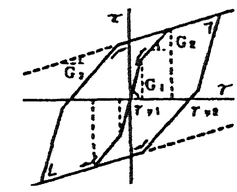


Fig.16 Stress - Strain Relationship of Concrete Panel

Table2 Mechanical Properties of Materials Used in The Analysis

	FR3	
$_cE$ =22163 MPa	$_c\varepsilon_B$=0.0037	$_c\sigma_B$=42.2 MPa
	FR3C	
$_cE$ =25301 MPa	$_c\varepsilon_B$=0.0030	$_c\sigma_B$=37.5 MPa
	Common to Both	
$_sE$=196133 MPa	E_p=98.1 MPa	α=49. MPa
$_s\sigma_y$=317.3 MPa	K_1=343. (1118.) MPa/cm	
G_1=5884. MPa	K_2=58.8 (215.7) MPa/cm	
G_2=4707. MPa	K_3=0.98 (15.7) MPa/cm	
G_3=5884. MPa	K_4=0.98 (4.9) MPa/cm	
τ_{y1}=4.9 (5.9) MPa	γ_{y1}=0.0005	
τ_{y2}=7.4 (9.1) MPa	γ_{y2}=0.003	
τ_{y3}=0.5 (0.5) MPa	( ) : for Joint Panel	

6 CONCLUSION

1) When a beam sidesway mechanism type reinforced concrete plane frame is deformed due to a horizontal force, all columns are identically deformed at an early stage. Thereafter, the beams are flexuously yielded, and then elongated in the direction of axis, but the footing beams were deformed only a little, resulting in the varying angles of the columns on the first floor. When the frame is receiving leftward monotonic loading, the angles of the columns on the first floor become greater as they are located closer to the left, resulting in a large difference between those at the left end and the right end. With the frame subjected to cyclic loading, the columns at the right end tend to be horizontally displaced towards the right, whereas those at the left end tend to be displaced towards the lefts.
2) Both monotonic and cyclic loading experiments demonstrated that the horizontal strength is greater than the horizontal strength already obtained using the ultimate bending moment obtained on the assumption that no axial force is generated in a beam. As the analysis

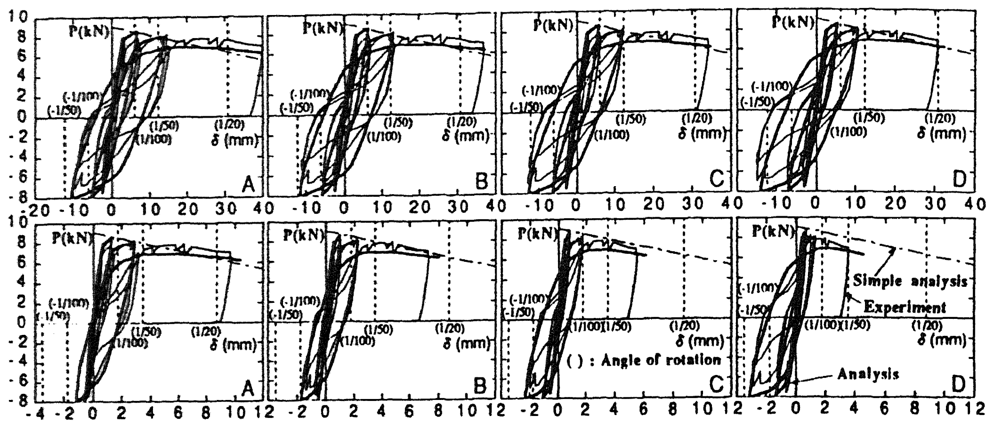


Fig.17 Horizontal Force - Horizontal Displacement Relationships

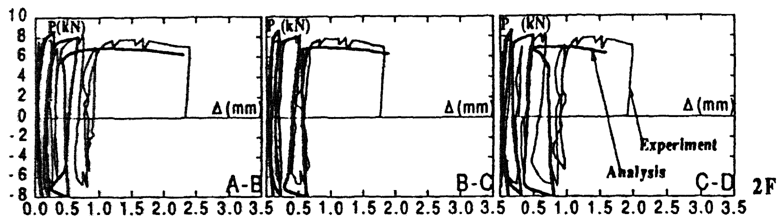


Fig.18 Horizontal Force - Axial Elongation of Beam Relationships

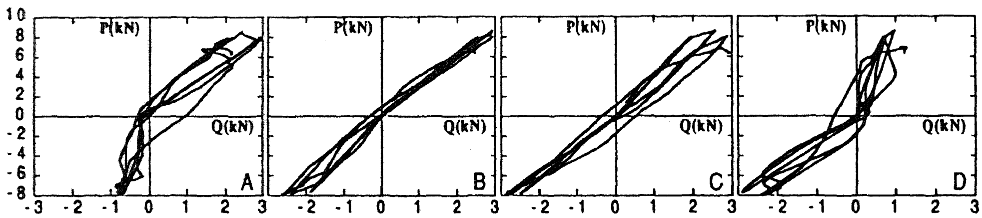


Fig.19 Horizontal Force - Shearing Force in Columns on The First Floor Relationships

results indicated, this was because the bending strength of the beams increased due to a compressive axial force.

3) In the reinforced concrete plane frame, the columns are subject to extra forced deformation due to the axial elongation of the beams that have been flexuously yielded, hence the sharing of the shearing forces in the columns at both ends of the frame is greatly varied. This phenomenon is noticeable in the columns on the first and second floors.

4) The present analysis results cover most details of the experimental results, and represent the behavior of the multi-story, multi-span reinforced concrete plane frame, taking into consideration the restraining effect of axial deformation of the beams flexuously yielded.

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