FUNDAMENTAL STUDY ON THE EFFECT OF VARIATION OF MATERIAL PROPERTIES ON THE FAILURE BEHAVIOR OF WHOLE STRUCTURAL SYSTEM

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SUMMARY

This paper describes the effects of variation of material properties on failure behavior of whole structure system by numerical simulation. In this study, we discuss the above mentioned issues in case of Reinforced Concrete structure which is composed of concrete and steel bars as main construction materials. First, effects of concrete are discussed. The effect of variation of concrete properties has a little effect on the bending failure behavior of whole structural system. However, from the investigation of failed springs in detail, it is observed that there are tendencies of failed concrete springs. In case of variation of stiffness of concrete, higher stiffness springs of concrete fail earlier. On the other hand, in case of variation of strength of concrete, springs of smaller strength fail first. Comparing bending failure test with shear failure test, the role of concrete material properties is larger in case of shear failure than in case of bending failure. By reducing the material properties of concrete, the deformation capacity is reduced drastically and brittle shear failure occurs. About the effects of reinforcements, material properties of steel affect the failure behavior of whole structural system greatly. In case of changing the stiffness of steel, it is observed that the area of distribution of failed springs becomes wider when stiffness is low and in case of changing the yield stress of steel, large and deep cracks propagate inside specimen when the yield stress is low. On the effects of concrete cover, when the concrete cover is small, many cracks appear at the surface of tension side and strength of whole structural system is reduced.

INTRODUCTION

In the past earthquakes, it has been reported that among the same type of structures designed and constructed in a same manner and located on the similar soil condition, one was collapsed or seriously damaged and the other was slight damaged. It is considered that one of the major reasons of this strong contrast is the variation of the material properties of structure. Particularly in case of Reinforced Concrete (RC) structure, variation of material properties is easily caused by construction environment, difference of steel locations and weathering of material in past time, etc. However, in most of structural analysis, the material properties are treated as constant. The effects of variation and spatial location of material properties on the failure behavior of whole structure are not considered directly. In this paper, effects of material properties on the failure behavior of whole structural system are investigated by numerical simulation. Using RC structure and members, parametric study is carried out by changing the stiffness and failure strength of concrete and steel. The difference of effects of changing material properties in case of different modes of failure, bending and shear failure, and the effect of steel location on the whole structural system are discussed, too.

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METHOD

Applied Element Method:

In this study, Applied Element Method (AEM), which is developed by Meguro and Hatem [2, 3], is used. In general, numerical methods of structural analyses can be divided into two groups. In the first group of the methods, material is considered as continuous, while in the other group, it is considered as discrete. The Finite Element Method (FEM) is the typical example of the former group and the Distinct Element Method (DEM) is that of the latter group. In the RC structural analysis using the first group methods like the FEM, discontinuity of the material like cracks is expressed using joint element or smeared crack model and the assumption of continuity can be kept. But in this manner, the algorithm of calculation is complicated and assumptions of location and direction of cracks are needed prior to the analysis. While using the second group methods like the DEM, accuracy of the analysis is less than that by the first group like the FEM in the range of small deformation. This is because of accumulation of numerical errors by explicit way. Above mentioned disadvantages don't exist in newly developed AEM. The method is simple but its result is very accurate in both small and large deformation range of behavior of structures. In this method, the structure is regarded as an assembly of small elements which are connected by two kinds of distributed springs in normal and tangential directions. From this assumption, the AEM doesn't have any restriction that elements are always continuous at the node. If the area composing the element, which is represented by a pair of normal and tangential springs, can't resist the acting stress, crack is automatically generated based on principal stress conditions. The change of stress condition due to cracks is distributed to neighboring springs. This method can easily follow crack initiation and propagation. In the terms of accuracy of analysis in small deformation range, it is reported that the AEM is much better than the DEM and comparable with the FEM [2]. The AEM can be applied to composite material like RC material with different reinforcement ratios. In the AEM, stress-strain relation curves of concrete and steel are defined individually and at the location of reinforcement, two pairs of springs, concrete springs and reinforcement springs in normal and tangential directions are used. This means that the reinforcement spring and concrete spring have the same strain and the effects of separation between reinforcement bars and surrounding concrete can not be easily considered within an element. However, when we look at the behavior of element collection as a unit, due to the stress conditions, separation between elements occurs because of failure of concrete springs before the failure of reinforcement springs and hence, relative displacement between reinforcement bars and surrounding concrete can be taken into account automatically. In the AEM, reinforcement springs can be set at the exact location of the reinforcement bars in the structural model. It should be emphasised also that effects of stirrups, hoops and concrete cover can be easily considered. In the FEM, material parameters of RC material are defined based on its reinforcement ratio and average values are used for elements. While in the AEM, total properties of RC material with any reinforcement ratios can be simulated automatically by combination of simple models of plain concrete, reinforcement and its arrangement.

Model of Specimen:

RC beam specimen of the size, 0.76m x 3.5m x 0.254m, is used for the analysis in Cases A-C (Fig. 1, Table 1) [4]. This specimen is divided virtually into 20 x 92 parts in vertical and horizontal directions, respectively, therefore, the size of the each element becomes 3.8cm x 3.8cm. In this study, 10 pairs of springs are assumed to connect two adjacent edges of the elements. It means that each spring represents the region of 0.38cm x 3.8cm. This 0.38cm x 3.8cm region is the minimum unit of the size by which the material properties can be controlled. Concentrated load is applied at the center of the beam by constant-rate deformation. First, the effect of variation of concrete properties on failure behavior of whole structure system is investigated. In this study, minimum unit of variation of material properties is set as the size of one element (3.8cm x 3.8cm). As the parameters discussing material properties of the element, failure strength and stiffness are considered. In Cases A-C, stiffness and strength are set individually and in Cases D and E (Fig. 2), they are considered correlated. In Case A, both stiffness and strength of concrete are constant, in Case B, stiffness is treated as variable and strength is kept constant, in Case C, strength is treated as variable and stiffness is kept constant. Normal distribution is assumed for the variation of material properties. Three cases, B/C-1, B/C-2, and B/C-3 with the coefficients of variation, 10%, 20% and 25% are considered for the analysis as shown in the Table 1, respectively.

Next, the effects of differences in the material properties on the failure behavior of different modes, bending and shear failure behavior, are investigated. The size of the specimen is 0.76m x 1.52m x 0.254m (Fig. 2) and this is modelled by 20 x 40 elements of 3.8cm x 3.8cm. Cross-section of the specimen and diameters of reinforcing steel bars are the same as those in Fig. 1. Material properties are also same as those in Cases A-C, which are set as basic material properties. Strength of concrete is set as half of the basic cases and stiffness is calculated from correlation between stiffness and strength of concrete. In Cases D and E, failure behavior in bending and shear are observed due to the change of material properties of concrete.

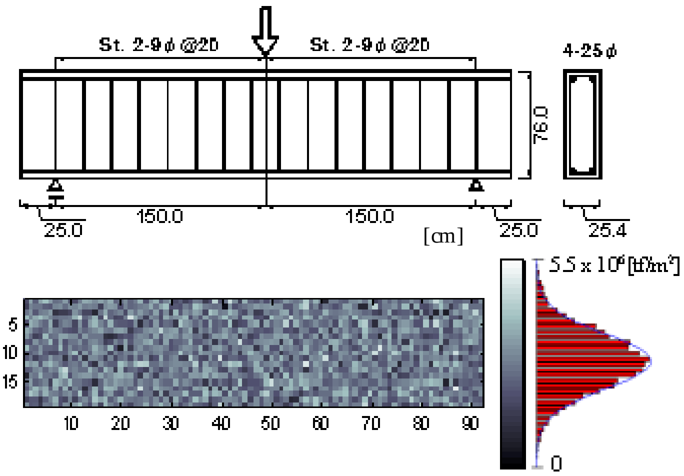

Fig. 1 Reinforcement Details and Spatial Distribution of Material Properties of Specimen (Case B-3)

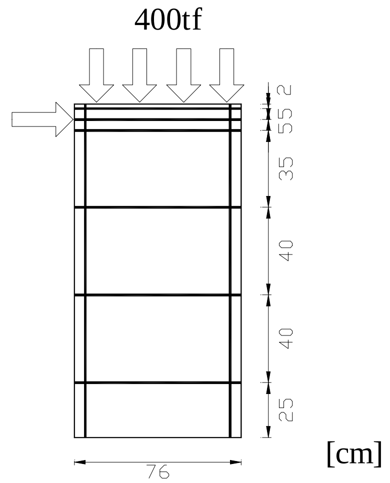

Fig. 2 Reinforcement Details of the Specimen in Case of Shear Failure Test (Cases D and E)

Table 1: Material Properties of Concrete

		Variation of Concrete Stiffness (Strength of concrete is constant.)			
	Coefficient of Variance	Constant	Cv = 10%	Cv = 20%	Cv = 25%
Variation of Concrete Strength (Stiffness of concrete is constant.)	Constant	Case A	Case B-1	Case B-2	Case B-3
	Cv = 10%	Case C-1	---	---	---
	Cv = 20%	Case C-2	---	---	---
	Cv = 25%	Case C-3	---	---	---

Table 2: Material Properties of Steel

			Stiffness of steel [tf/m^2]			
			Main steel	0.95 x 10^7	1.90 x 10^7	2.85 x 10^7
Yield stress of steel [tf/m^2]			Stirrup	1.07 x 10^7	2.13 x 10^7	3.20 x 10^7
	Main steel	Stirrup	Ratio of material properties	1/2	1	1.5
	22,300	14,250	1/2	---	Case J-1	---
	44,600	28,500	1	Case I-1	Case A	Case I-2
	66,900	42,750	1.5	---	Case J-2	---

Finally, the effects of material properties and location of steel bars on the failure behavior of whole structural system are investigated. Material properties and location of steel bars that are used in Cases A-C are set as basic case. In Cases I and J, stiffness and yield strength are varied, respectively. Material properties of the steel are 0.5 and 1.5 times of the basic cases (I/J-1, I/J-2) as shown in Table 2. In Case K, the concrete cover to the main reinforcement is increased by 10cm compared to basic case.

RESULTS OF ANALYSIS

Effects of Variation in Concrete Material Properties

a) Bending Failure Test

Comparison of Case A with Case B is done using load-displacement curves (Fig. 3). Although we use very large coefficients of variation (10-25%) of concrete stiffness, Fig. 3 shows that the effects of variation in stiffness on the failure behavior of whole structural system are very small. Similar phenomenon is observed in the comparison between Cases A and C. The failure modes in Cases A-C are all bending failure type. This means that tensile load is carried mainly by steel, and hence, the failure behavior is controlled by steel bars. Figure 4 shows the displacement-number of failed springs relation. From the investigation of material properties of failed springs, typical tendencies are observed due to increase in the coefficient of variation of concrete. It is observed from the results that the higher the stiffness of concrete spring becomes, the earlier the spring fails (Fig. 5). On the other hand, in case of variation in strength of concrete, the smaller the strength is, the earlier the spring fails (Fig. 7). These tendencies can be seen more clearly in the graphs (Figs. 6 and 8). Contours of these figures show the ratio of the number of failed springs to all springs in certain class interval of material properties (See Fig. 1).

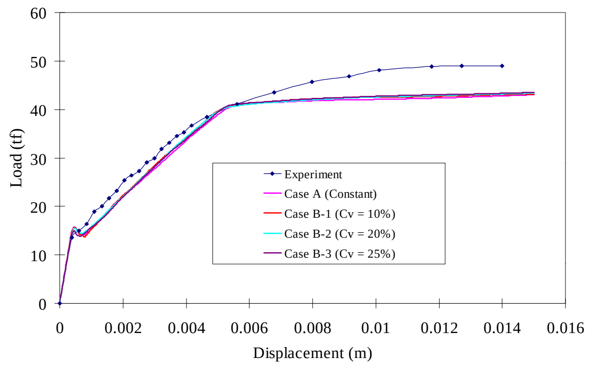

Fig. 3 Load-Displacement Curve (Variation of Stiffness of Concrete)

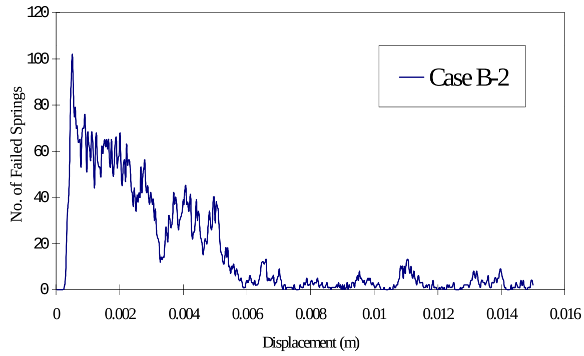

Fig. 4 Displacement-Number of Failed Springs Curve (Variation of Stiffness of Concrete)

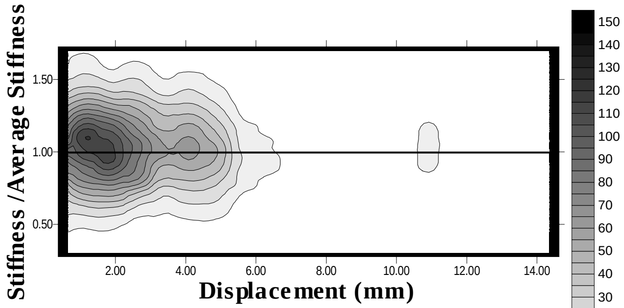

Fig. 5 Contours Showing Number of Failed Springs (Case B-2, Cv = 20%)

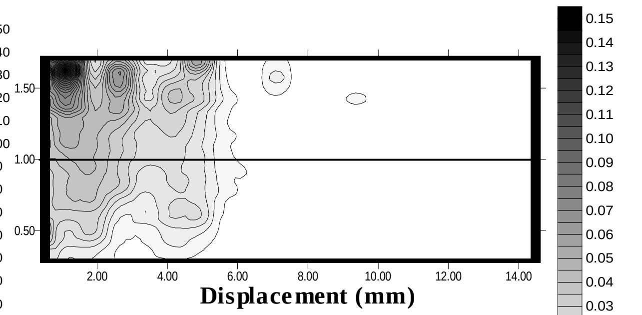

Fig. 6 Contour Showing the Ratio of Number of Failed Springs (Case B-2, Cv =20%)

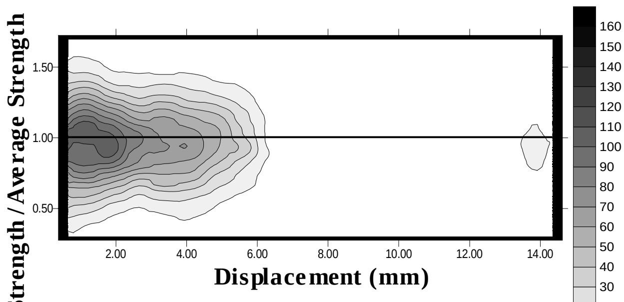

Fig. 7 Contour Showing Number of Failed Springs (Case C-2, Cv = 20%)

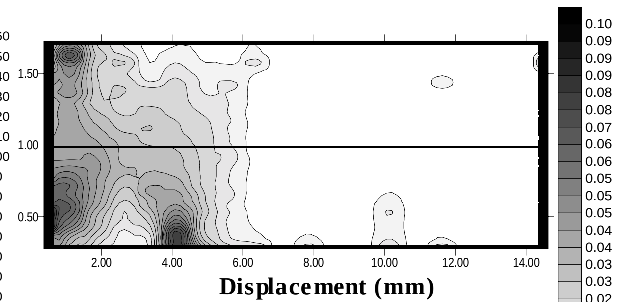

Fig. 8 Contour Showing the Ratio of Number of Failed Springs (Case C-2, Cv = 20%)

b) Effects of Concrete Properties in Different Failure Modes

Figures 9 and 10 show the load-displacement curves of different failure modes, bending and shear failure. From these figures, it can be found that the reduction of material properties of concrete in case of shear test has larger influence on the failure behavior of whole structural system than in case of bending test. It can be said that concrete plays an important role in case of shear failure. Moreover, the specimen in Case E deforms much more than that in the basic case as shown in Fig. 11. The specimen in the basic case fails in ductile manner. While the deformation capacity of specimen in Case E decreases drastically and the specimen fails in brittle manner.

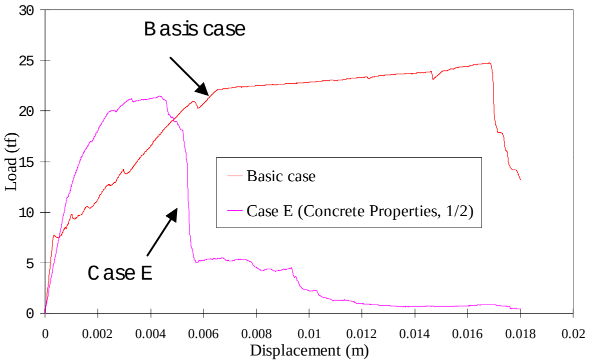

Fig. 9 Load-Displacement Curve in Case of Shear Failure Test

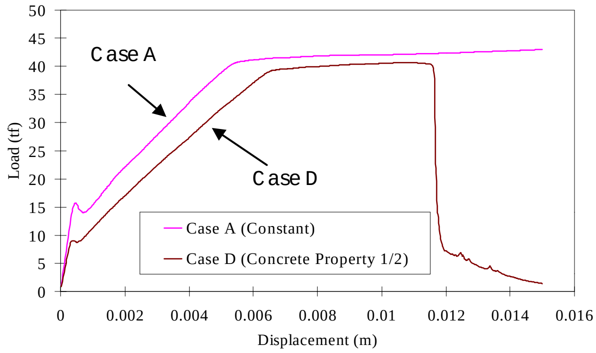

Fig. 10 Load-Displacement Curve in Case of Bending Failure Test

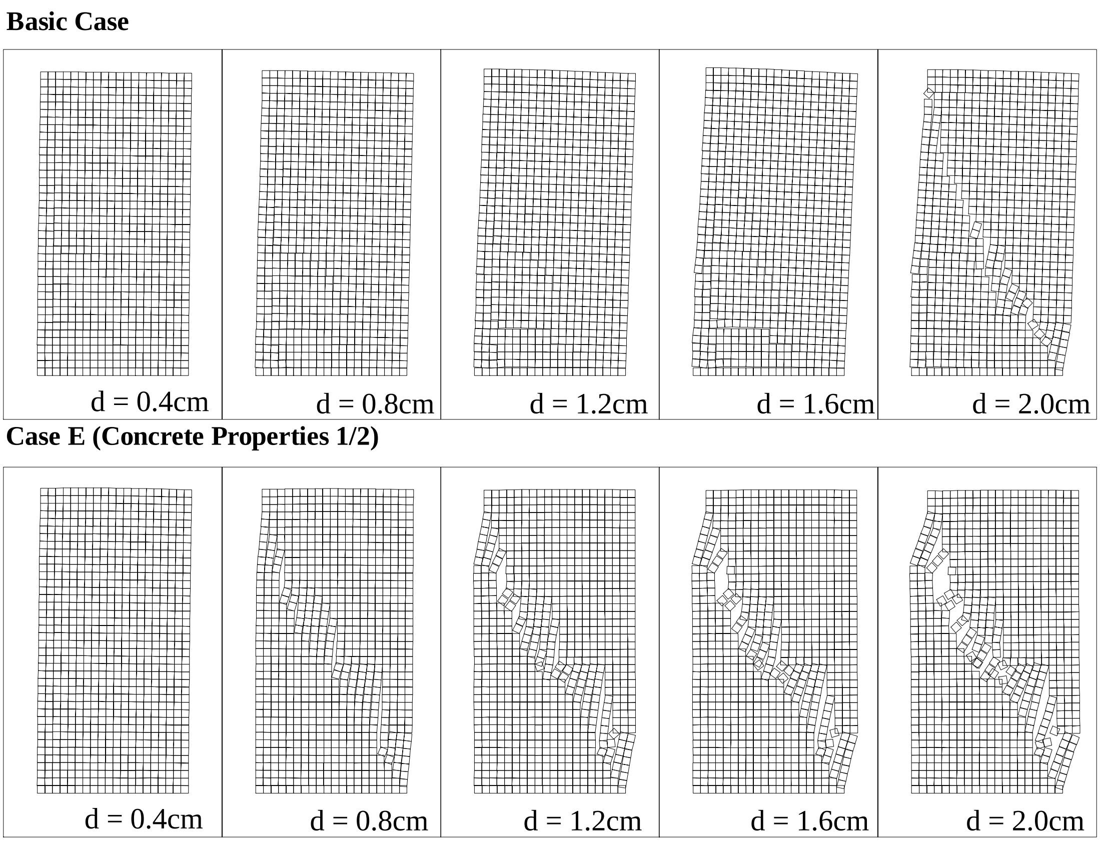

Fig. 11 Comparison of Deformation and Crack Patterns in Different Failure Modes

Effect of Steel Properties

Figure 12 shows the load-deformation curves varying in the stiffness of steel. The differences among all cases are small till starting point of concrete failure. It is because the steel is bonded with concrete and resists the load. But after concrete failure starts, steel should bear larger load, so steel properties affect failure behavior of whole structural system. As the stiffness of steel is smaller, the tangent of load-displacement curve is small. Yield strength of whole structural system becomes lower if stiffness of steel is reduced inspite that yield stress of steel is constant. It is because that the number of failed springs increases till steels yield when the stiffness of steel is reduced. Figure 13 shows the spatial distribution of failed concrete springs in cases of changing stiffness. It is found that the area of failed concrete springs becomes wider if the stiffness of steel is low. As the stiffness of steel becomes lower, the deformation inside specimen becomes larger against same applied load and this affects more up to deep part of specimen.

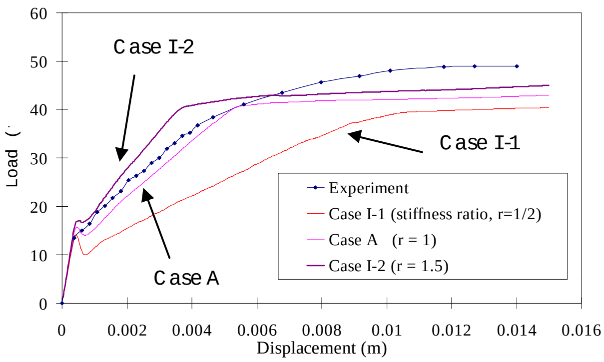

Fig.12 Load-Displacement Curve in Case of Changing Stiffness of Steel (Case I)

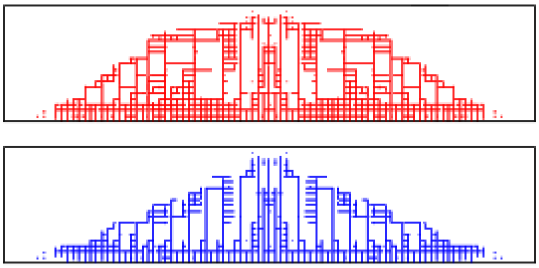

Fig. 13 Distribution of Failed Springs at Displacement, d=12mm (Effects of Stiffness of Steel, Upper: Case I-1, Stiffness Ratio, r=1/2, Bottom: Case I-2, r=1.5)

Figure 14 shows the load-deformation relations in case of changing only yield stress of steel bars. The deformation at the starting point of plastic deformation becomes smaller if yield stress of steel becomes lower. All cases of load-deformation curves go through same path still steel starts plastic deformation. As the stiffness of steel is constant in all cases, whole structural stiffness is same in every case. Figure 15 shows the spatial distribution of failed springs in cases of changing yield stress of steel. A tendency is found that tension failure reaches up to deep part of the specimen, as yield stress is lower. Steel easily yields at the small deformation and the load borne by steel becomes less when the yield stress of steel is small. From this mechanism, the steel deformation increases locally and load which concrete should bear becomes large causing increase the local deformation.

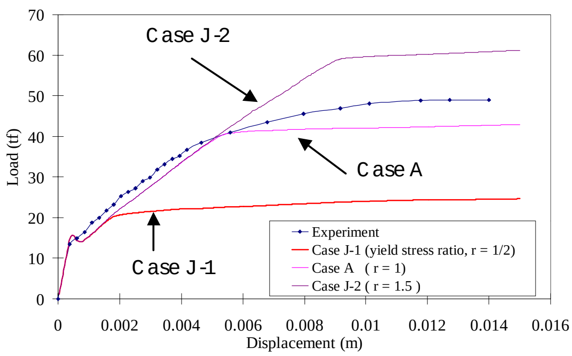

Fig. 14 Load-Displacement Curve in Case of Changing Yield Stress of Reinforcements (Case J)

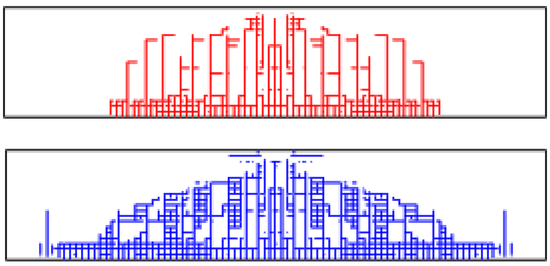

Fig. 15 Distribution of Failed Springs at Displacement, d=12mm (Effects of Yield Strength of Reinforcement, Upper: Case J-1, Yield Stress Ratio, r =1/2, Bottom: Case J-2, r=1.5)

Effect of the Concrete Cover

Figure 16 shows the load-displacement curves for different concrete covers. From the figure, we can say that the effects of changing concrete cover on the failure behavior are small till the starting of failure of concrete. But after failure of concrete, this effect becomes significant because only steel bars bear the major load. Increasing the concrete cover, that is change of location of main reinforcement to deeper inside of the specimen, makes the stiffness of whole structural system small, especially after starting of concrete failure. Figure 17 shows the spatial distribution of failed springs of concrete. The load that steel bars bear becomes relatively small and concrete bears more load. Therefore, the strength of whole structural system is reduced. Many fine cracks of concrete springs appear at the surface of tension side if the concrete cover is small. On the other hand, large and deeper concrete cracks appear sparsely at the surface of tension side if the concrete cover is large.

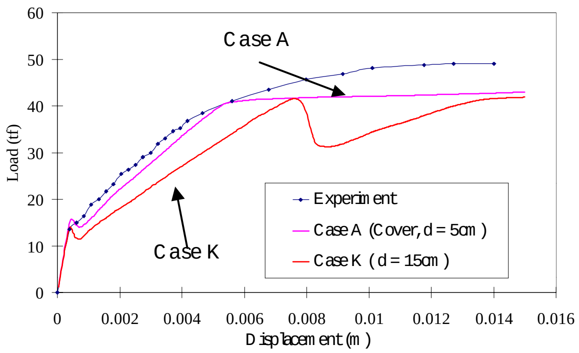

Fig. 16 Load-Displacement Curve in Case of Changing Concrete Cover (Case K)

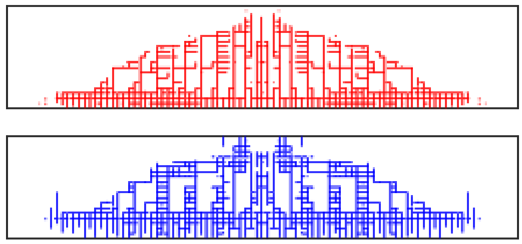

Fig. 17 Distribution of Failed Springs at Displacement d=12mm (Effects of Concrete cover, Upper Case A, d=5cm, Bottom Case K, d=15cm)

CONCLUSIONS

In this study, the effects of variation of material properties on the failure behavior of whole structural systems are studied by the Applied Element simulation. We discuss the mechanism of failure behavior of RC structural members by changing the stiffness and failure strength of concrete and reinforcing steel bars. Major results obtained through the study are summarised below.

- The effects of variation of material properties of concrete such as strength and stiffness on the bending failure behavior of RC structural system are minor.
- From the detailed investigation of failed springs, it is observed that there are tendencies of failed concrete springs. In case of variation of stiffness of concrete, concrete springs of higher stiffness fail earlier. On the other hand, in case of variation of strength of concrete, springs of lower strength fail first.
- Based on the comparison of bending failure test with shear failure test, the role of concrete material properties in case of shear failure test is larger than that in case of bending failure test. By reducing the material properties of concrete, deformation capacity is drastically reduced and brittle shear failure occurs.
- The material property of steel affects greatly on both bending and shear failure behavior of whole RC structural system.
- In case of changing the stiffness of steel, it is observed that when the stiffness of steel is small, the load which steel bars bear becomes small. Therefore, concrete should support large load instead of steel and hence, the area of distribution of failed springs becomes wider.
- In case of changing the yield stress of steel bars, when the yield stress of steel is small, steel yields at the smaller deformation and the deformation of whole structural system becomes large. As the result of the mechanism, tension failure of concrete becomes predominate.

- In case of changing the concrete cover, when the concrete cover is large, the load which steel bars bear is relatively reduced and large and deep tension cracks of concrete appear at the surface of tension side sparsely. The strength of whole structural system becomes lower.

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