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Structural Behaviors of Deep RC Beams under Combined Axial and Bending Force

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Abstract

This paper presents experimental studies of deep reinforced concrete (RC) beam behaviors under combined axial and bending loads. In order to investigate the effect of axial loads on the structural behaviors of the deep RC beams, specimens are prepared to have different shear span-to-depth ratios and subjected to axial loads of 235kN or 470kN. From the experiments, structural behaviors such as failure modes, load-deflection relationships, and strains of steel bar and concrete are observed. As results, for the deep beam with shear span-to-depth ratio of 0.5, load at the beam failure decreases as applied axial load increases, while the deep beams with shear span-to-depth ratios of 1.0 and 1.5 show that the applied axial load delays the beam failure. In addition, failure mode of the deep beam changes from shear failure to concrete crushing due to compressive stress at the top corners of RC beams as shear span-to-depth ratio decreases. From the experiments, it is important to notice that deep beam with relatively small span-to-depth ratio under axial load shows early failure due to concrete crushing, which cannot be directly applied to widely known design method for deep beam, strut-to-tie model.

Keywords: Deep RC beam, axial load, failure mode, deep beam design

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1 INTRODUCTION

Deep beams in mega structures have been recently used, as needs of high rise building with high performance structures have been increased. Because classical flexural beam theory cannot be used to understand structural behaviors of deep beams, many researchers have reported their experimental/ analytical studies to investigate structural behaviors and develop design methods of the deep beams.

Ramakrishnan and Ananthanarayanana(1968) investigate structural behaviors and ultimate shear strength of simply supported deep beams. From the experimental results, an equation for predicting the ultimate shear strength of deep beams is proposed using splitting coefficient K. In their study, K of 1.12 is chosen from the lower bound of possible K ranges regardless of specimen size, shape, and loading conditions. Smith and Vantsiotis(1982) examine structural behaviors and strength of deep beams depending on vertical and horizontal web reinforcement and shear span-to-depth ratio. From their experiments, it is found that the vertical web reinforcement improves ultimate shear strength, while horizontal web reinforcement had little or no influence on ultimate shear strength.

Design method of deep beams has been developed by many research groups, such as ACI (American Concrete Institute) and committee members in Euro code. Design codes of ACI and Euro code provide guide to design deep beams considering shear behavior. The former design guide defines deep beam which satisfies at least one of the following conditions: 1) clear span is equal to or less than four times the overall member depth, or 2) regions with concentrated loads are within twice the member depth from the face of the support. On the other hand, Euro code defines a deep beam if the span is equal or longer than 3 times the overall section depth. In order to design deep beam and predict its ultimate shear strength, using strut-and-tie models are recommended generally by ACI and Euro code. Aguilar et al.(2002) investigate behavior of RC deep beams in terms of initial flexural cracking, initial diagonal cracking, initial yield of longitudinal reinforcement, and failure. They also predict shear strength using ACI318-99 building code and compare with predictions from ACI318-02 building code. The former code doesn't consider strut while the latter code does. Their conclusion is that both ACI318-99 and ACI318-02 are shown to be conservative, while the strut-and-tie model provided in ACI318-02 results less conservative. Matamoros and Wong(2003) develop an equation to understand relationship between the strength and the applied force in the main strut and ties of deep beam. The proposed equation is also used to predict shear strength of the deep beam. The proposed equation predicts shear strength and shows good agreements with the experimental results. Quintero-Febres et al.(2006) report experimental studies in order to find out strut strength factors in concrete struts and compare them with provisions in Appendix A of the ACI-02 building code. The experimental results show that the strut strength factors in Appendix A of the ACI-02 are adequate for normal strength concrete, but not for high strength concrete. According to their study, ACI-02 code predicts ultimate shear strength approximately 10% higher than the experimental results in high strength concrete. In addition minimum effective reinforcement ratio of 0.01 is suggested in high strength concrete. Arabzadeh et al.(2009) investigate the effect of concrete softening effect caused by web reinforcement in addition to strut-and-tie mechanism. Even though it is widely known that the web reinforcement has beneficial effects on deep beam behavior, their experimental results show that it is important to choose optimized amount of web reinforcement for effective behavior of the deep beam. According to their study, amount of web reinforced can be determined with a consideration of strength of concrete, span-depth ratio, and ratio of tensile main reinforcement. In addition, they propose a formulation that can predict ultimate shear strength of the deep beam, which includes concrete strength, arrangements, amount of web reinforcement, and shear span-to-depth ratio. The ultimate shear strength value predicted from the proposed formulation is compared with predictions from the existing equations proposed by other researchers including ACI318-05 and CSA(Canada Standards Association), and the experimental results. Even if many researchers have studied about deep beams and proposed design methods, there are relatively few studies about the effect of axial loads on structural behaviors of deep beams.

Currently, deep beams have been widely used in high rise buildings with mega structures. In these cases, deep beams are often subjected to lateral loads from wind and earthquake. However, there has been lack of information about behaviors of deep beams subjected to axial loads. Therefore, this paper aims at examining structural behaviors of deep beams subjected to axial load and bending. Deep beams are prepared to have shear span-to-depth ratios between 0.5 and 1.5 and the variables are shear span-to-depth ratios and magnitudes of applied axial loads. From the experiments, structural behaviors and failure modes of the deep beams under axial loads and bending are observed.

2 EXPERIMENTAL METHOD

In order to investigate structural behaviors of deep beam, four point bending tests are performed on deep beams subjected to axial force.

2.1 Tested specimens

For the experiments, reinforced concrete deep beams are fabricated. Cross section of the beam is 200×700mm and the length is 3200mm. Mixture ratio of the concrete is listed in Table 1 and concrete strength is about 28MPa. For reinforcement, D22 and D32 which average yield strength is 400MPa are used as longitudinal compression bars and longitudinal tension bars, respectively. The longitudinal reinforcement is extended beyond the supports and terminated with 90 degree hooks to provide adequate anchorage. All beams are reinforced by horizontal and vertical web reinforcing bars at uniform intervals. Details of the reinforcement for the test specimens are illustrated in Figure 1. Main variables are 1)shear span-to-depth ratios of 0.5, 1.0, and 1.5, and 2)axial loads of 235kN and 470kN as listed in Table 2. The axial loads are calculated from 6% and 12% of maximum load capacity of the deep beam.

Table 1: Mixture ratios of concrete

Compressive strength (MPa)	W/C (%)	s/a (%)	Weight per unit vol. (kg/m^3)				
			W	C	S	G	AD
28	46.9	47.7	141	354	882	944	1.77

Table 2: Summary of specimens

Specimen Name	Variables	
	Shear span-to-depth ratio	Axial force (kN)
5C0	0.5	0
10C0	1.0	0
15C0	1.5	0
5C1	0.5	235
10C1	1.0	235
15C1	1.5	235
5C2	0.5	470
10C2	1.0	470
15C2	1.5	470

2.2 Test setup

For loading test, the beams are simply supported and subjected axial and bending loads as illustrated in Figure 2. In order to prevent floating of the beam due to the axial force, bending load of 30kN is applied to the beam before applying axial load. The applied axial load is maintained during the test, and the rest of bending load is applied monotonically until the beam reaches failure. Linear variable differential transformers (LVDTs) are placed at the bottom surfaces of the beams to measure the displacements at the center and ¼ of the beam length. Strain gages are also placed on beam surfaces in the middle of the beam length and on steel bars between loading point and support point.

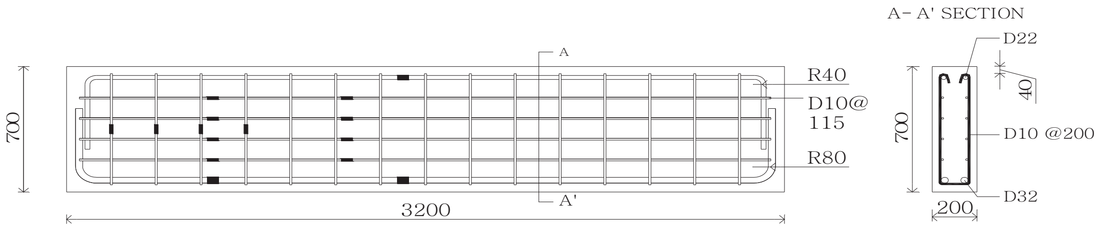

Figure 1: Elevation and cross sectional details of deep beam (Steel gauges are marked as ▬ .)

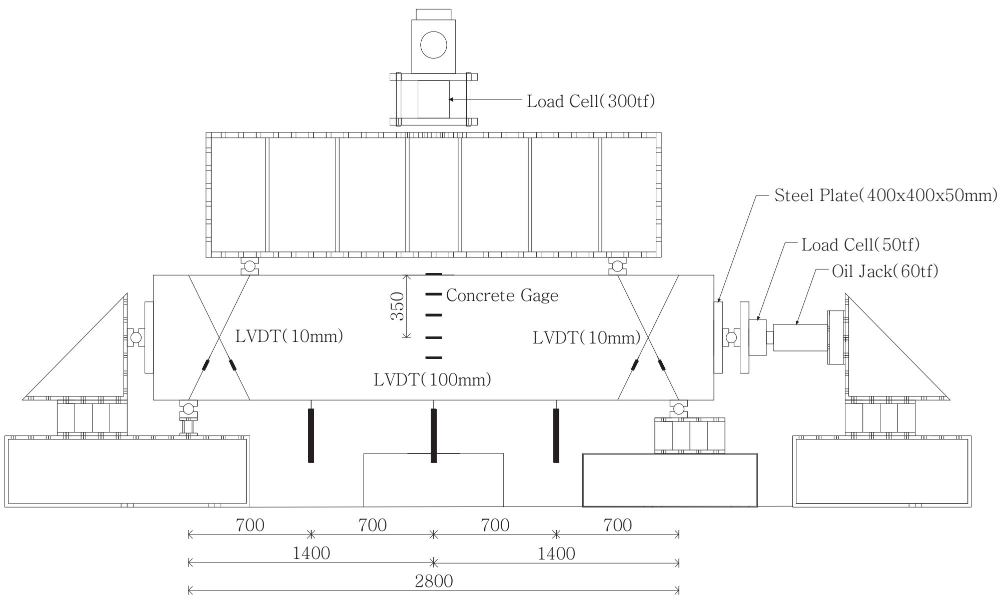

Figure 2: Test setup (length unit is mm.)

3 RESULTS

3.1 Load-deflection relationships

From the experiments, relationships between load and deflection of the tested beams are obtained as illustrated from Figures 3(a) to (f). Plotted deflections are measured at the center of the beam span using the LVDT placed on the bottom surface of the beam. The effect of shear span-to-depth ratio on the structural behaviors of the beams can be found from Figures 3(a), (b), and (c). Regardless of axial load, the stiffer load-deflection curves are obtained from the beams with the smaller shear span-to-depth ratios. Also, the beams with the smaller shear span-to-depth ratios are failed at the lower level of deflection compared with the beams with the larger shear span-to-depth ratios. This indicates that beams become brittle as the shear span-to-depth ratio decreases. In addition, the effect of the applied axial loads on the structural behavior of the tested beams is investigated. From Figures 3(d), (e), and (f), it is commonly found that the slope of load-deflection curve increases, as the axial load increases. It is also found that for the beams with shear span-to-depth ratios of 1.0 and 1.5, maximum load at beam failure increases as axial load increases. This is because the axial force reduces tensional stress on the bottom of the beam, therefore, is able to delay the beam failure due to bending. However, when the shear span-to-depth ratio is 0.5, the axial loaded beams are failed at lower load level with smaller deflections compared with the unloaded beam. Quantitatively speaking, maximum load of 5C2 specimen decreases about 12% compared with maximum load of 5C0 specimen due to early failure by concrete crushing. Also, deflection of 5C2 specimen at failure is only about 55% of 5C0. For 10C2 and 15C2 specimens, axial load is beneficial for the beams under bending such that maximum load of 10C2 and 15C2 is increased by 23% and 20% compared with 10C0 and 15C0, respectively.

3.2 Failure modes

The failure modes of the selected beam specimens are seen from Figures 4(a) through (d). The concrete crushing occurred in 5C1 and 5C2 can be found from Figures 4(a) and (b), respectively. The beam subjected to the larger axial load (5C2) show larger area of concrete crushing compared with 5C1. Other beams, such as 10C1 and 15C2, are failed due to shear failure, and large cracks along the line between support and loading points are observed as seen in Figure 4(c) and (d).

4 CONCLUSIONS

In this study, structural behaviors of deep beams under combined axial and bending load are investigated. The deep beams are prepared to have different span-to-depth ratios from 0.5 to 1.5 and subjected to axial loads of 235kN and 470kN. Conclusively speaking, when the shear span-to-depth ratio decreases with increased axial load, the deep beam is failed due to concrete crushing before shear failure is occurred. These experimental results indicate that early failure of the beam is occurred due to concrete crushing when the deep beam is under axial load with relatively small shear span-to-depth ratio.

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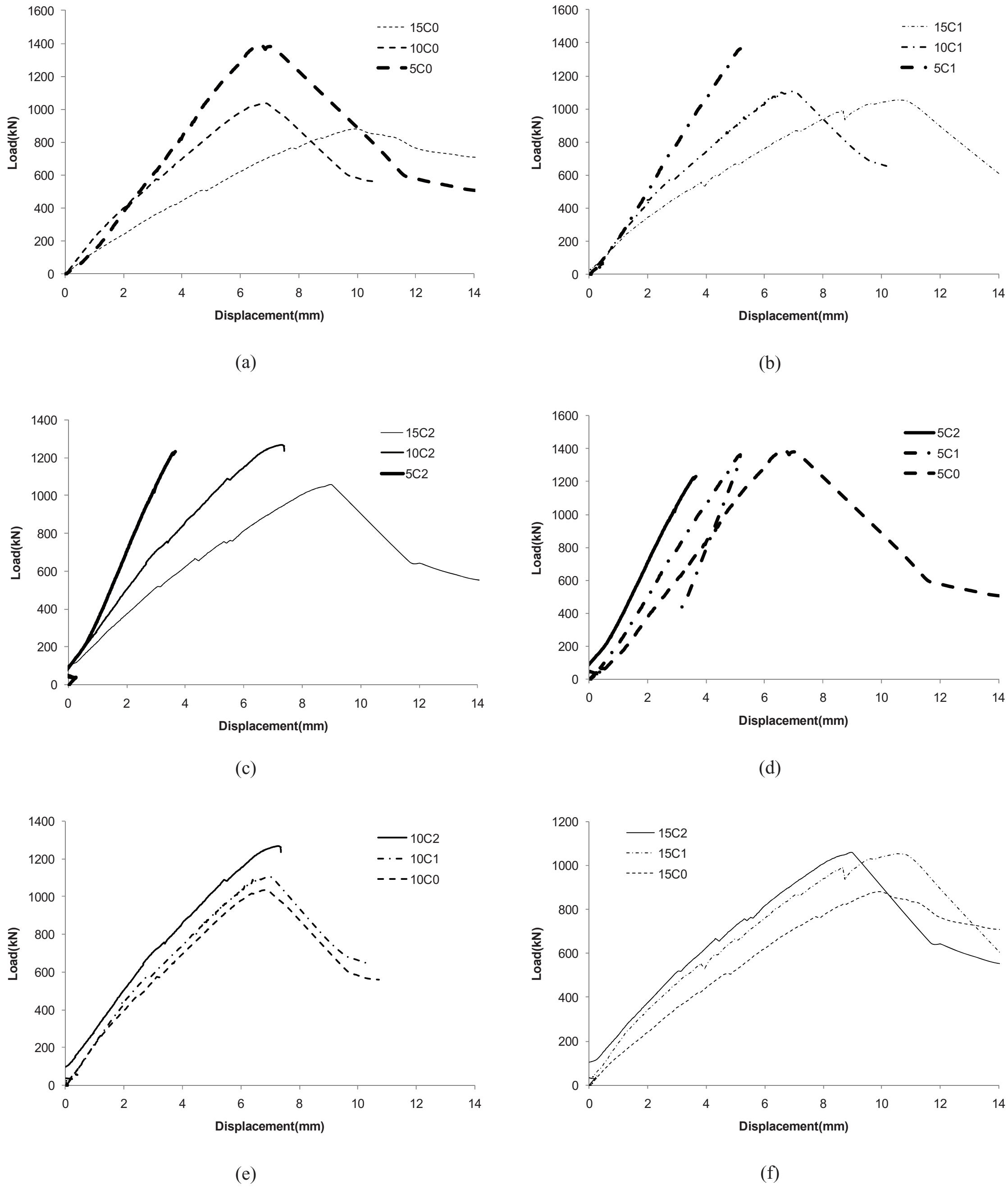
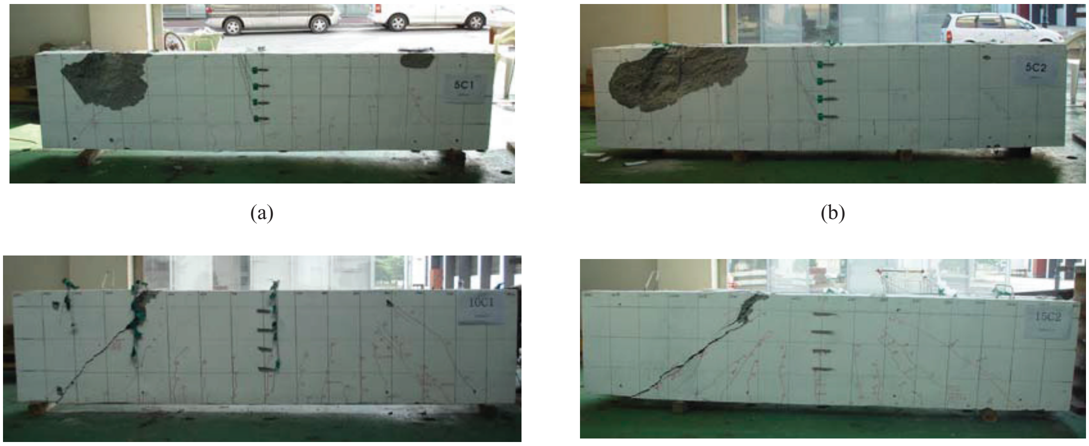


Figure 3: Load-deflection relationships of the tested beams; (a) without axial load, (b) with axial load of 235kN, (c) with axial load of 470kN, (d) shear span-to-depth ratio=0.5, (e) shear span-to-depth ratio=1.0, and (f) shear span-to-depth ratio=1.5.



(a) (b)

(c) (d)

Figure 4: Failure of tested beams; (a) 5C1, (b) 5C2, (c) 10C1, and (d) 15C2.

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