
Published paper

Son, K.S., Pilakoutas, K., Neocleous, K. (2006) *Behaviour of concrete columns with drilled holes*, Magazine of Concrete Research, 58 (7), pp. 411-419
http://dx.doi.org/10.1680/macr.2006.58.7.411

Behaviour of Concrete Columns with Drilled Holes

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Date Written: **January 2005**

Date Corrected: **September 2005**

Number of Words: **2,800**

Number of Tables: **0**

Number of Figures: **17**

Abstract

Holes drilled out to install additional services or equipment, such as for ducts through columns, beams, or walls, can lead to loss of strength and possible structural failure. Until now little work has been done on holes in columns and, hence, this study aims to examine the amount of strength lost due to the presence of holes in columns. The reported experimental work deals with different parameters such as the number and dimensions of the holes and their relative position. It is shown that, for large diameter holes, a section capacity loss up to 50% is possible.

Keywords: concrete structures, columns, strength and testing of materials

Notation

F_i	Column’s load-carrying capacity.
F_n	Load-carrying capacity of control columns.
f_{ci}	Compressive stress predicted for each column by using the maximum value of compressive strain (ε_c), measured in the tested columns.
f_{cm}	Experimental mean compressive strength obtained for each column by testing concrete cylinders.

1. Introduction

Openings and drilled holes are often provided in concrete structural elements to allow access for services, such as pipes for plumbing and electric wiring (Fig. 1). The provision of such openings may result in the loss of strength, stiffness and ductility and, hence, significant structural damage may be sustained, if the provision of the openings is not considered adequately during the design or construction stages. This is especially true for un-braced structures, since loss of stiffness leads to redistribution of internal forces and moments.

The mechanical behaviour of concrete beams and slabs with openings has been examined in several studies [1 to 6] and design rules have been recommended [7, 8]. However, in the case of concrete columns and walls with transverse openings, minimal research has been carried out and, currently, there is a lack of appropriate design rules. Columns are critical elements, but in general only carry a fraction of their capacity at normal service loads. Though the provision of a few small holes may not create problems in the majority of cases, failure due to weakening of the section can be brittle and lead to catastrophic results. Hence, extreme care is required when the safety of columns is affected by post-design actions (Fig. 2).

The research reported in this paper aims to investigate the compressive resistance-capacity of concrete columns with transverse drilled holes. Nine columns with different holes were tested experimentally to evaluate the effect of hole geometry and location. Analysis of the experimental results is used to derive appropriate design recommnedations.

2. Experimental Methodology

Eight concrete columns with different holes and one column without holes were cast to evaluate the effect of section loss on the compressive resistance-capacity. Two samples were cast for each type of column. The parameters examined experimentally were the diameter, relative position, and amount of holes; Fig. 3 shows the details of the holes provided in each column. All columns were 1600mm long, 300m deep and 200mm wide and contained both longitudinal and transverse reinforcement. The longitudinal reinforcement comprised six, 13 mm in diameter, rebars and the transverse reinforcement consisted of shear links, 10mm in diameter. The spacing of the shear links was 50 mm and 168 mm at the ends and the middle of the column, respectively. A clear concrete cover of 30 mm was provided in all column specimens and a strengthening jacket (shown in Fig. 4) was provided at both ends of each column in order to minimise the effect of local buckling of the longitudinal reinforcement as described in a later section. The depth and thickness of each jacket were 160 and 20 mm, respectively.

2.1 Material Characterisation

The characteristic value of yield stress of both longitudinal and transverse reinforcement was 400 MPa. The compressive strength of the concrete was monitored by control cylinders, 200 mm long and 100 mm in diameter.

All column and cylinder specimens were cast from the same batch of commercially supplied ready-mix concrete (Seoul, Korea), whose target, 28-day, strength was 23.5 MPa. Normal weight concrete was used with a maximum aggregate size of 25mm. The water to cement ratio was 0.55, and the cement used was ordinary-Portland-cement with pulverised-fly-ash. The average slump was 100mm. The specimens were cast in timber moulds and were compacted with electrical vibrators.

2.2 Curing Procedure

One day after casting, the column and cylinder specimens were demoulded and cured in a construction site (in Seoul, Korea) until the day of testing. The average-day curing temperature ranged from 21.1 to 25.5 degrees Celsius, while the air-moisture content ranged from 57 to 92.6%.

2.3 Test Procedure

The cylinder specimens were tested 28 days after casting. The average compressive cylinder strength was found to be 20.2 MPa, which is slightly lower than the design strength. The columns were tested 36 days after casting by using a standard compressive loading procedure. The applied load was manually controlled and increased step by step at 20 kN increments. A steel plate (200x300x20mm) was placed on top of each specimen in order to distribute the load, which was applied through a pair of hinges along the x-axis, in the middle of the top and bottom surfaces of the column (Fig. 5).

The actuator itself was hinged in the y-direction, at the point of reaction with the frame. In all cases, the front side corresponded to the bottom of the specimens as cast.

3. Test Results

3.1 Failure modes

Initial testing on a column without holes (termed “control”) demonstrated that failure initiated due to local buckling of the longitudinal reinforcement (Fig. 6). This type of failure is common place in such specimens due to inadequate support for the longitudinal rebars at their termination. In practice, the column reinforcement will be continuous into the next storey and, hence, these end-problems should be avoided. To eliminate this type of failure, the remaining columns were strengthened at both ends by steel jackets (Fig. 4 and 5). Although, as shown in Fig. 7 for the second control column, the jacket-strengthening did not completely eliminate the weakness at the interface between the concrete and compressive rebars, failure due to buckling of the reinforcement was avoided. In this case, the tensile strains - induced on the side of the column at the location of the rebars (see Fig. 7) - caused concrete crushing in the compression zone (back-side).

As expected, in all columns, bending occurred towards the front, since the back-side of the column had marginally weaker concrete and, hence, went into compression. There is also a strong possibility that this tendency was encouraged by shrinkage strains, which are expected to be higher in the side exposed more to the environment during curing (the back-side). The shrinkage strains can lead to a small bowing of the column and provide the initial imperfection necessary to force buckling always in the same direction. Though in practice, columns are cast vertically and, hence, there is no difference in the concrete quality between the front and back of the column, material and geometric imperfections will always exist. Thus, the results can be considered to be relevant.

The provision of even one hole resulted in concrete crushing at the level of the hole. This is shown in Fig. 8 and 9 for specimens ED3H1-UB and ED5H1, respectively; the hole in the former specimen is eccentric, while the hole in the latter specimen is central. In both cases, and indeed in all cases with holes, the location of the tensile cracks was clearly influenced by the presence of the holes. Similarly to the control columns, splitting cracks appeared in the two columns at the level of the reinforcement, due to the weakness at the interface between concrete and the compressive reinforcement. In all cases with holes, crushing failure of columns took place in the vicinity of the holes. A typical failure pattern, shown in Fig. 9, indicates that cracks spread into the compression zone from splitting initiated near the edges of the column at the reinforcement level.

Figures 10 and 11 show for specimens ED3H2L and ED5H2, respectively, that columns with two holes sustained a similar type of failure as columns with one hole.

3.2 Load deformation response

Fig. 12 shows typical load versus lateral-deflection curves for each type of tested columns. The presented lateral deflection is the average of the deflections measured at the front and back of each column. The results do not indicate any particular pattern in the behaviour of columns with holes, apart from the apparent reduction on the compressive resistance-capacity. In most specimens, the reduction in the resistance-capacity (in comparison with control specimens) was around 9 to 21%, but a 46% reduction was sustained by one of the samples of ED5H2 (Fig. 13). It is worth notining that the resistance-capacity of one of the ED3H1UB samples did not sustain any reduction.

3.3 Strains in concrete and reinforcement

Figure 14 shows typical load-strain profiles for the control specimens as well as for columns containing 5 cm holes. The location of the strain gauges is shown in Fig. 4. In specimen ED5H2, the steel strain gauge is on the front of the section rather than the back. The central curves represent the average of the concrete gauges on the left and right. In some of the specimens (e.g. ED5H2L), there is indication of some bending in the z-x plane of the column, but overall most of the bending took place in the z-y plane (out of plane). The strain profiles show that, despite the P-δ effects, the columns remain in compression, at least in the middle section. There is no evidence of the longitudinal reinforcement yielding and in general the back-side of each column did not reach the strain level of 0.002 for maximum stress in compression. Similar results were obtained for the columns containing 3 cm holes. However, it is noted that two samples (ED3H1UB and ED3H2L) attained the pure compression-strain limit in the back-side of the column.

4. Analysis

As expected, the main affect of the holes is a reduction in the column load-bearing capacity, δF (equation 1). However, as seen from the strain diagrams in Fig. 14 and 15, there is also a reduction in the concrete strain in compression. By using the stress-strain model of Eurocode-2[9], the strain loss can be converted into a stress loss (δf_c), as shown in equations 2 and 5. The relation between δF and δf_c is shown in Fig. 16. It can be seen that a stress loss of up to 20% can be inflicted by holes (such as in specimen ED5H2)

$$\delta F = 100(1 - \frac{F_i}{F_n}) \tag{1}$$

$$f_c = f_{cm} \frac{kn - n^2}{1 + kn - 2n} \tag{2}$$

$$n = \frac{\varepsilon_c}{\varepsilon_{c1}} = \frac{\varepsilon_c}{-0.0022} \tag{3}$$

$$k = 1.1 \frac{E_{cm}\,\varepsilon_{c1}}{-f_{cm}} = 1.1 \frac{9500\ \sqrt[1/3]{f_{cm}}\ (-0.0022)}{-f_{cm}} = \frac{22.29\ \sqrt[1/3]{f_{cm}}}{f_{cm}} \tag{4}$$

$$\delta f_c = 100(1 - \frac{f_{ci}}{f_{cm}}) \tag{5}$$

It is clear that the stress reduction in the mid-section is a result of failure at the weakened section. Hence, it is natural to examine δF against the loss of cross-sectional area (δA) at the level of the holes, as shown in Fig. 17. Interestingly, the figure shows that the reduction in capacity is directly proportional to the cross-sectional loss.

This is not a surprising result, but before this is adopted for design purposes, it is worth discussing the key issues relating to holes in structural elements, such as uncertainty. Though results on average give an almost perfectly linear relationship between loss in stress and area, the coefficient of determination (R-squared value of trend-line) is not very high. There are a number of reasons for that:

a) Natural variability. Concrete compressive strength has a natural variability of around 6 Mpa for ready-mix concrete from the same batch[10] and this value can be up to 8 Mpa for a specific mix.

b) The hole creates a stress concentration around it and this may further amplify the effect of the section loss. Hence, to take into account the above, the reduction in load-bearing capacity can be evaluated by equation 6. The calculated values for δF correspond to 98% confidence level for the mean and are similar to the 98th percentile.

$$\delta F = \delta A + 6 \quad \text{(as percentage)} \tag{6}$$

5. Discussion

Instability

It is clear that holes are not the cause of initial instability, which leads to second-order bending effects, but their presence will almost certainly accelerate instability in slender columns. However, overall the stiffness reduction affected by small holes is unlikely to change the buckling characteristics of columns in any significant manner. Codes of practice (such as the CEB-FIP[11] model code and Eurocode-2[9]) take into account instability by classifying (according to slenderness bounds) isolated elements into slender or non-slender, and structures and other structural elements to braced or sway. The Korean code of practice states that a stiffness–reduction factor of 0.7 should be adopted for slender, rectangular concrete columns. It is recommended that the effect of large holes is taken into account in the slenderness bounds, but this aspect is beyond the scope of this study.

Damage around holes

It should be noted that the holes in this study were pre-formed with plastic tubes and, hence, there was little damage inflicted to the columns. An additional reduction in strength may be necessary due to hammer drilled holes, depending on the nature of drilling and concrete strength.

6. Conclusions

This study investigated the effect of transverse holes on the compressive resistance-capacity of reinforced concrete columns. The experimental results showed that the provision of holes in columns leads to a loss of the column load-bearing capacity and their analysis concluded that this loss is directly proportional to the loss of area. It is recommended that the reduction in column capacity is assessed against the design actions, and if necessary, remedial strengthening in the region of the holes will need to take place. Furthermore, it was stated that holes may accelerate the instability effects of slender columns and, hence, it is recommended that codified slenderness bounds need to take into account the effect of large transverse holes.

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Figure Captions

Figure 1. Holes drilled in concrete column (wall type) to allow passage for building services

Figure 2. Earthquake damage sustained by column containing vertical pipe

Figure 3. Details of holes provided in each column specimen

Figure 4. Experimental setup for column specimens

Figure 5. Hinge above top surface of column

Figure 6. Local rebar buckling failure of column without holes and jacket-strengthening

Figure 7. Cracking pattern for control column with effective jacket-strengthening

Figure 8. Typical cracking pattern for column ED3H1UB (eccentric hole)

Figure 9. Typical cracking pattern for column ED5H1

Figure 10. Typical cracking pattern for column ED3H2L

Figure 11. Typical cracking pattern for column ED5H2

Figure 12. Typical axial load versus mid-span lateral deflection curves

Figure 13. Normalised compressive load for all column specimens

Figure 14. Typical load versus strain curves for columns with 5cm holes and a control column

Figure 15. Typical load versus strain curves for columns with 3cm holes

Figure 16 Correlation between load reduction and stress reduction

Figure 17. Effect of area reduction (due to the presence of holes) on the compressive resistance-capacity of the columns