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"Punching shear of slab-column connection in flat-plate construction."

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ABSTRACT. The flat plate system is currently widely used in construction. It permits architectural flexibility, more clear space, less building height, easier formwork, and shorter construction time. However, there remains the problem of brittle punching failure due to the transfer of shearing forces and unbalanced moments at the flat plate-column connection. It is the purpose of this paper to investigate the effects of various interdependent factors that govern the punching shear resistance and behaviour of the flat plate-column connection, as well as their inclusion in current Codes.

Keywords: Flat plate concrete, Punching shear, Reinforced concrete, Code provisions.

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INTRODUCTION

The flat plate system has been widely used in construction. It permits architectural flexibility, more clear space, less building height, easier formwork, and shorter construction time. In Australia, the proportion of flat slab floors in low-rise and medium-rise construction from six to ten stories is considerably higher than 50 percent [1]. However, flat plates do have limitations. High shear stresses around the supporting columns, due to the transfer of shearing forces and unbalanced moments between slabs and columns, can lead to abrupt and catastrophic punching shear failure at loads less than the flexural design capacity. Many flat plate structures have collapsed in the mode of punching failure, especially during earthquakes [2, 3]. Thus punching failure in flat plate system is a major design concern and effective solutions to avoiding punching failure are of great importance. The purpose of this paper is to provide an insight into the governing factors influencing the punching shear resistance and behaviour of the flat plate-column connection, as well as their inclusion in current Codes.

FACTORS INFLUENCING THE PUNCHING SHEAR RESISTANCE AND BEHAVIOUR OF FLAT-PLATE SYSTEMS

Concrete Strength

The compressive strength of concrete has a strong influence on the punching shear strength and behaviour of flat slabs [4, 5]. The shear strength of a flat slab is currently assumed to be proportional either to the square root or to the cube root of the concrete compressive strength. The former is adopted by ACI318-02 [6] and AS3600 [7] while the latter by BS8110 [8] and CEB-FIP MC90 [9].

However, this power relationship may be higher for slabs with small shear span-to-depth ratio, implying a stronger influence of the concrete compressive strength on the punching shear strength. When testing punching shear on column footings [10], it was found that the punching shear strength was proportional to the concrete compressive strength to the power of 0.76.

Regan and Braestrup [5] concluded that both the cube and the square root dependencies are adequate since the variability of these predictions is also influenced by differences in the dependence upon other factors such as reinforcement ratio, slab depth and position of shear perimeter.

For normal strength concrete, when investigating experimentally a large number of circular flat plates with the concrete strength ranging from 14 to 56 MPa, Gardner [4] found that the cube-root relationship between shear strength and concrete strength is preferable to the square-root relationship. The former results in a better correlation with the experimental data. The cube-root relationship between shear strength and concrete strength is also recommended for high strength concrete by Marzouk and Hussein [11].

Moreover, as the concrete strength increases beyond 40-50 MPa, most current approaches become less conservative and even unsafe in some cases [12]. This is partly because for high strength concrete, the relationship between the shear resistance of a member and the strength of the concrete depends upon the characteristics of the aggregate [9]. If the aggregate fractures at a crack, leaving smooth crack surfaces, the shear resistance may be below the predicted values that are based upon results for normal strength concrete.
Besides, the increasing strength of concrete also brings about other changes [13]:

1. The ultimate deflection and deformation as well as the rotation capacity and moment capacity increase significantly when high-strength concrete is used, especially for specimens subjected to high moments.
2. The displacement ductility, the rotation ductility, and the energy-absorption capacity increase significantly when high-strength concrete is used.

Flexural Reinforcement

Generally, the ultimate punching capacity increases with the addition of steel reinforcement. Marzouk and Hussein [11] noticed an increase in the ultimate applied load by 2.4 times as the reinforcement ratio increased from 0.49% to 2.37% for slab of 120 mm thick. Similar capacity enhancement of 1.8 times was also observed for slab thickness of 150 mm when the steel ratio varied between 0.64% and 2.33%. However, ductility is adversely affected by the increase in steel reinforcement ratio. Increasing the reinforcement ratio from 1.1% to 2.3% and from 1.2% to 2.4% for slab thickness of 150 and 120 mm decreased the ductility by 46% and 22%, respectively [11].

The influence on ultimate punching capacity of the addition of steel reinforcement was further investigated by Kuang and Morley [14]. It was found that punching shear strength was enhanced significantly as the reinforcement ratio increased from 0.3% to 1%. The corresponding increases were 51% for the slabs with 40 mm thickness and 68% for those with 60 mm thickness. Nevertheless, when the percentage of steel was over 1%, there was little increase in the nondimensional punching shear strength. This indicates that the steel reinforcement has an important effect on the punching shear strength for lightly reinforced restrained slabs, but little effect on those heavily reinforced. The punching shear enhancement with increasing steel ratio also holds true for high-strength lightweight concrete slabs under cyclic loading, as presented in [15]. It was found that the punching shear capacity increased by 50% as the steel ratio increased from 0.5% to 1.0%. As expected, the reinforcement ratio also influences the slab’s crack pattern. The crack widths of the heavily (1.6%) and normally (1.0%) reinforced slabs were smaller than those of lightly reinforced slabs (0.3%) [14].

Slab Depth

The ultimate punching capacity is directly proportional to the square of effective depth, as demonstrated in [16] and [11]. Thus, small absolute variations in effective depth would produce significant differences in punching shear resistance. This highlights the importance of accurate placement reinforcement in practice. However, as increasing the slab thickness will increase the dead load accordingly, net gains in strength obtained by increasing the slab thickness might be less than proportional to the square of effective depth. Where dead load makes up a substantial portion of the total load, these net gains are only approximately linearly related to effective depth [17].

Size Effect

The load-deflection diagram of a slab without stirrups exhibits a gradual decline rather than a plastic yield plateau [18]. The larger the slab thickness, the steeper the post-peak decline of the load-deflection diagram. Thus, the punching shear behaviour of thinner slabs is closer to plasticity, and that of thicker slabs is closer to linear elastic fracture mechanics. For either slab, the failure is inevitably brittle and not plastic. Because of the brittleness of failure, plastic limit analysis theoretically ceases to be applicable and the size-effect law for blunt failures, in theory, should apply [18].

Boundary Condition

When a slab is restrained against lateral expansion, membrane compressive forces are developed. Membrane action is generally considered as a secondary effect that occurs after cracking of the concrete or yielding of the reinforcement, and has been found to result in substantial enhancement in the load-carrying capacity of restrained concrete slabs [14]. For normally reinforced slabs of 1.0% reinforcement ratio, when the width of edge beams increased from 70 to 280 mm, the corresponding enhancements of ultimate nondimensional strength were approximately 46% and 64% for slab thicknesses of 40 mm and 60 mm, respectively. However, the effect for lightly reinforced slabs of 0.3% reinforcement ratio was less noticeable with the corresponding increase of only 13%. Compressive membrane forces also play an important part in the control of slab deflection and cracking. As the degree of slab restraint increases, the value of slab deflection decreases, and the cracks are finer, narrower but larger in number [14].

Span-to-Depth Ratio

Generally, it is expected that the punching strength will be influenced by the span-to-depth ratio if the failure extends to the support, whereas the span-to-depth ratio would be of no consequence if the failure is fully contained within the slab. This has been experimentally demonstrated [19]. While the normalized punching shear strength remained relatively constant for span-to-depth ratios of 6, 8 and 12, it increased significantly as span-to-depth ratios decreased from 6 to 2 [19]. The increases in shear strength were 247% and 102% for specimens without and with shear reinforcement, respectively. Observed during the experiment [19] was evidence of the formation of compression struts between the point of application of the load and the support as specimens approached failure. Thus, a tied-arch mechanism similar to that observed in deep beams may have developed.

Column Size

Test results [11] clearly indicate that as the column size increases both ductility and stiffness increase accordingly.

Openings

Openings in the vicinity of columns may be required for ducting. They are detrimental to the punching shear capacity of the slab to various extents depending upon location and size. An opening located at the front of the column decreases the shear capacity of the connection more than the same size opening located at the side of the column [20]. This may be explained by the fact that the opening at the side face of the column has a smaller effect on the area and the inertia of the critical shear section. The distance between the column face and the opening also influences the capacity of the connection. The further the opening from the column face, the less detrimental effect it exerts on the punching shear capacity of the slab [20].

In addition, as expected, the size of the opening affects the punching capacity of the slab. The ultimate strength of the slab with the larger opening is less than that with smaller one [20].

Loading Type

Concrete shear strength under cyclic, especially cyclic reversed moment transfer, is less than that under monotonic loading [21]. This is partly because the flexural reinforcement bars, in the yield range, undergo the Bauschinger's effect, which causes the steel in repetitive cycles to yield at a much lower stress than the initial yield strength. Thus, deformations of steel bars will excessively increase and more loss of aggregate interlock takes place than for the case of monotonic loading. Cyclic reversed loading also results in propagation of flexural cracks all over the slab depth, which weakens the concrete compressive zone and reduces the amount of shearing forces the slab can resist [21].

Gravity Load

Increasing the slab gravity load significantly reduces the capacity of the connection to transfer unbalanced moment, as well as lowers the lateral drift attained prior to failure and the stiffness of the connection [3, 21-23].

Shear Reinforcement

Shear reinforcement, in general, is intended to make failure occur at larger load preceded by larger deflections in a more ductile manner. Conventionally, shear reinforcement can be in the form of stirrups or bent-up bars. However, these types of shear reinforcement have proven not to be very effective, especially in thin slabs (150-250 mm in overall thickness) [1, 24, 25]. Structural shear heads have also been used extensively since mid 1930's and are included in many codes [1]. Stud shear reinforcement was introduced and has become widely-accepted as an effective and efficient measure to improve punching shear strength and ductility [3, 26]. Recently, novel forms of shear reinforcement, such as inclined stirrups [25], steel plates and steel bolts [27], or the combination of bent bars and stirrups [28], have produced effective and promising shear reinforcing systems, which not only result in desirable ductile behaviour under load but also are suitable for standard practice usage.

DISCUSSION ON THE INCLUSION OF INFLUENCING FACTORS IN CODE PROVISIONS

Current code procedures are essentially empirically based. They adopt the simple "shear on certain critical perimeter" approach and involve only the most important parameters [6-9]. This results in a divergence among Code provisions, even though the same experimental results have been used by most code writing bodies in formulating their provisions. The reason lies in the differences in the interpretation of the research, the philosophy on resistance, load factors adopted, as well as local construction practice.

The influence of concrete strength is adopted differently, as presented above. Also, current code provisions are based upon empirical relationships developed mostly from tests on low and normal strength concrete, and thus may be less conservative and even unsafe when applied to high strength concrete slabs [12, 13].

In addition, current Codes have yet to take into account effects of factors such as types of shear reinforcement, edge restraint, density of concrete, cyclic loading and span-to-depth ratio. This is especially the case for shear reinforcement, where different types of shear reinforcement of various degrees of superiority are being used. That means the values given in the codes have to be conservative if all cases are to be covered.

The influence of the flexural reinforcement ratio on shear capacity is not explicitly included in AS3600 [7]. Instead, AS3600 relies on detailing requirements to ensure sufficient flexural reinforcement in the zone immediately over the column. In contrast, CEB-FIP Model Code [9] explicitly includes this significant effect.

To demonstrate the differences between approaches in current codes, the unfactored ultimate shear strength of an interior slab-column connection in four two-way flat-plate systems are compared (Table 1). Concrete strength is assumed to be 40 MPa and slab depth 350 mm. The flexural reinforcement is distributed in accordance with AS3600 [7], with 85% of the negative moment carried in the column strip and the remaining in the middle one. The results are tabulated in Table 1.

The results show a significant variation in the ultimate shear strength as predicted by the Codes, with differences of up to 60%. For the three systems with 400x400 mm columns, AS3600 [7] and ACI318-02 [6] predict a constant ultimate shear strength. The ultimate shear strength predicted by CEB-FIP Model Code [9] varies according to reinforcement percentage and span. As expected, the capacity by CEB-FIP Model Code increases with increasing reinforcement ratio and span. Most significantly, for Systems 1 and 3, strengths predicted by AS3600 are 30% to 60% greater than those by CEB-FIP Model Code. Only when the reinforcement ratios are large do CEB-FIP Model Code and AS3600 predictions converge. For System 2, which has a significant percentage of reinforcement, the predicted values are essentially the same. Comparing Systems 1 and 4, where column size varies, AS3600 continues to overpredict but by a lesser amount of 21%.

Table 1 Ultimate shear strength predicted by Codes.

	SYSTEM	CEB-FIP MODEL CODE 1990 (kN)	AS3600-2001 & ACI318-02 (kN)	DIFFERENCE (%)
1)	9x9 m grid 400x400 mm column Steel ratio of 0.75%	1385	1806	- 30.4
2)	9x9 m grid 400x400 mm column Steel ratio of 1.67%	1809	1806	+ 0.2
3)	9x6 m grid 400x400 mm column	1130	1806	- 59.8
4)	9x9 m grid 650x 250 mm column Steel ratio of 0.75%	1407	1710	- 21.5

<u>Note</u>: - Results for System 3 are inferred from System 1.
- Reinforcement ratio is averaged across the design strip.

CONCLUSION

The punching shear resistance and behaviour of the flat plate-column connection are affected by various factors. The factors include concrete strength, flexural reinforcement, slab depth, size effect, boundary condition, span-to-depth ratio, column size, openings, type of loading, gravity load and shear reinforcement.

Current Codes provisions are essentially empirically based, with very simple formulae involving only some important parameters. The ultimate shear strength predicted by different Codes may differ significantly, which has been clearly demonstrated by the example in the discussion above. Codes such as AS3600 [7] which do not rationally incorporate the influence of primary variables such as reinforcement ratio, appear to require revision.

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