

# Punching Shear in Pad Foundations on Rock

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**ABSTRACT:** With the increasing popularity of multi-storey buildings, foundation engineering is becoming a more important issue in the construction industry. In Malta, sound rock can normally be found at shallow depths. However, the design codes in use locally suggest a generic design process for foundations which does not take into account the type of substrate. The focus is on critical failure modes affecting reinforced concrete pad foundations on soils. The controlling parameter in the design of these foundations is found to be punching shear. The physical properties of sound rock under load suggest that a pad foundation on rock will exhibit a different behaviour than that predicted by codes.

This dissertation is meant to encourage and lead the way to further research in this field of study. A review of the recommendations given by BS 8110: Part 1 (1985), Eurocode 2 prEN 1992-1-1 and ACI 318-02 on pad foundations, with particular emphasis on punching shear was first carried out. It was found that, only Eurocode 2 prEN 1992-1-1 outlines briefly the issue of pad foundations on rock. An experimental research was also carried out with the aim of finding the actual concrete punching shear resistance of footings on rock. Results were compared to theoretical predictions drawn up following recommendations given by each of codes considered. Experimental results demonstrate that pad foundations on rock have a significantly higher resistance to punching shear failure than predicted by the codes.

## 1 INTRODUCTION

### 1.1 *Punching Shear*

Punching Shear occurs when an area is subject to a concentrated state of stress relative to its immediate surroundings. Failure can occur either by pure punching or by bending induced punching where, the initial tension cracks will grow tangentially to form the punching surface. The cracked profile of the punched area indicates the mode of failure.

Fig 1. Shear Load - Schematic crack patterns which illustrate load-carrying behaviour in the state of failure (Staller M.A. (2000))

Concrete Design Codes associate the behaviour in shear of flat slabs and pad foundations. A similar load distribution is assumed, the only difference being in the orientation.

Fig 2. Flexural Load - Schematic crack patterns which illustrate load-carrying behaviour in the state of failure (Staller M.A. (2000))

The perimeter which lies outside the loaded area, defined by the punching shear perimeter, will be sub-

ject to a force acting opposite to the applied load. The two sections will try to move in opposite directions creating a shear stress in the concrete which will fail at the weakest plane.

### 1.2 *Pad Foundations on Soil*

Heavily loaded pad foundations on soils with low bearing pressures are most susceptible to failure by punching shear. In this case, the bearing area required will have to be outside the 45° angle of dispersal of load and will have to distribute load, by bending, to the entire footing area.

Fig 3. Load Distribution on a Pad Foundation

A uniform load distribution is assumed beneath the footing, but in practice a non-uniform stress distribution occurs. These differences in soil pressure will, in time generate an uneven settlement, accompanied by more bending, triggering a premature punching shear failure.

Fig 4. Punching Failure

### 1.3 Pad Foundations on Rock

The local construction industry benefits from the fact that most construction sites are founded on sound rock, therefore nearly all pad foundations are built directly on rock. It is local practice to design to British Standards which require checks for bending, vertical shear and punching shear at a distance of  $1.5d$  from the column face and at the column face. In most circumstance it is punching shear which is the critical factor in the design of the footing. A considerable increase in depth will be required to act against punching resulting in a hefty increase in construction cost.

The differences in properties between soils and rock imply a different behaviour under load. In rock, load is transferred by bearing through the area formed by the  $45^\circ$  angle of dispersion. If the rock is relatively incompressible and experiences no settlement, the base of the foundation can never bend. Therefore no load will be transferred to the area outside the critical perimeter formed by the angle of dispersion through the depth of the pad foundation. At ultimate load the underlying rock can fail in one of three ways. The failure load for in situ rock is presumably higher than the compressive failure load obtained through compression tests, this being due to tri-axial confinement of the rock in its natural state. Safe bearing pressures given in codes underestimate heavily the performance of rock because they are generalized recommendations and take into account any weaknesses to which the specific type of rock may be susceptible to. If the type of rock failure is limited to crushing under the footing, the pad foundation may still not be subject to sufficient bending to induce punching shear.

### 1.4 Outline of Dissertation

The aim of this study is to open up a discussion and investigation into the punching shear failure criterion for foundations built on rock. To this end an analysis and comparison of the recommendations given given by three codes; namely BS 8110: Part 1, Eurocode 2: (Final Draft prEN 1992-1-1) and ACI 318-02, on punching shear was carried out. An experimental program was also carried out to test and compare the theoretical results obtained with those obtained from presently available codes of practice.

## 2 RESULTS

### 2.1 Theoretical Results

Through the comparisons carried out it is interesting to note that Eurocode 2 (prEn 1992-1-1) already

considers the design of foundations on rock. However, no design guidance on punching shear or bending is given in this case. Instead the code recommends a design against a splitting force. The foundation takes the shape of a thicker column to spread loads over a larger area and the reinforcement shown is similar to that used for a column.

The dissertation illustrates procedures and recommendations given by the three codes considered, primarily on the subject of shear and punching shear. The variables governing punching shear were compared by the use of spreadsheets and the results obtained were plotted to illustrate differences in values obtained from one code to the other. Results obtained for Eurocode 2 (prEn 1992-1-1) and BS 8110: Part 1(1985) are similar and for both the concrete shear stress is calculated by determination of a number of variables. The approach suggested by ACI 318-02 to punching shear seems to be more of an empirical approach depending mostly on concrete compressive strength. This leads to an over estimation of concrete shear stress which is then compensated for by the somewhat smaller critical perimeter which balances out when calculating the shear strength of concrete, bringing the values of all three codes within the same range.

Fig 5. Comparison of Critical Perimeters

### 2.2 Experimental Results

Experimental results showed all three modes of failure in pad foundations, namely failure by bending, by punching shear, and by direct shear at the column face.

Fig 6. Experimental Setup

It was observed during testing that; the first footing FN-1, supported on line supports at the perimeter of the foundation, failed in bending due to lack of tensile reinforcement in it. FR-1 was supported in the same way as for FN-1 but this time the footing was adequately reinforced against bending. Failure of FR-1 eventually occurred due to punching shear which occurred at a higher load than those predicted by the codes. The final footing FR-2 was supported on a continuous surface formed by limestone blocks and failed by punching at the column face only when the column was reduced in size and a void was left underneath the column. The same had been tried before with no void underneath and the footing had not punched. It is felt that the support conditions in all tests carried out played a very important part in the eventual mode of failure.

Fig 6. Punching Shear in FR-1

The experiments conclusively show that footings are safer on rock because punching shear as predicted

by the present codes cannot take place. However, further testing is required for validation and verification of alternative design procedures.

### 2.3 Recommendations for Future Work

The experimental program carried out in this study compares the behaviour of a pad foundation supported on its edge to the behaviour of pad foundations supported on rock. The behaviour on rock could be further compared to the behaviour on soil by constructing a large container to house various cohesive and non cohesive soils which would be contained and under pressure and would thus develop a limited triaxial stress state. Because of the unpredictability of the type of failure and the magnitude of the failure loads required it is suggested that the experimental footings be of smaller dimensions than the ones used in this study. The issue as to whether or not bending reinforcement is required may also be taken into consideration.

### 2.4 References

ACI Committee 318. (2001). ACI 318-02: Building code requirements for structural concrete. American Concrete Institute.

BS 8110 (1985). Structural use of concrete. Part 1: Code of practice for design and construction. British Standard Institution.

Eurocode 2. (1992). Design of concrete structures - Part 1-1: General rules and rules for buildings. Portland Cement Association

Goodman, R.E. (1989). Introduction to Rock Mechanics (second edition) John Wiley & Sons

Hallgren, M., Kinnunen, S., & Nylander, B. (1999). Punching Shear Tests on Column Footings Royal Institute of Technology, Department of Structural Engineering, Stockholm, Sweden.

MacGinley, T. J. & Choo, B.S. (1997). Reinforced Concrete, Design Theory and examples. London: E & FN Spon.

Manning, G.P. (1972). Design and Construction of Foundations Cement and Concrete Association

Mosley, W. H. & Bungey, J. H. (1990). Reinforced Concrete Design. London: Butterworth – Heinemann.

Neville, A. M. (1995). Properties of concrete. London: Addison Wesley Longman Limited.

Ngo, D. T. (2001). Punching shear resistance of high-strength concrete slabs. University of Melbourne, department of Civil and Environmental Engineering.

Portland Cement Association (2002). Notes on ACI 318-02: Building code requirements for structural concrete. Portland Cement Association

Sistonen, E., Lydman, M., & Huovinen, S. (1997). The geometrical model of the calculation formula of the punching shear capacity of the reinforced concrete slab. Rakentajanaukio 4, 02150 Espoo, pp 95, app. 23.

Staller, M. A. (2000). Analytical studies and numerical analysis of punching shear failure in reinforced concrete slabs. Stockholm: Royal institute of technology, TRITA-BKN, Bulletin 57.

Tomlinson, M.J., R. Boorman (2001). Foundation Design and Construction. Prentice Hall.