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Punching shear failure in blast-loaded RC slabs and panels

J. Sagaseta [a,*], P. Olmati [a,1], K. Micallef [a,2], D. Cormie [b]

[a] *Department of Civil and Environmental Engineering, University of Surrey, Guildford GU2 7XH, UK*
[b] *Resilience Security and Risk, Arup, London, UK*

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ABSTRACT

Reinforced concrete (RC) slabs and panels are commonly encountered in critical infrastructure and industrial facilities with a high risk of close-range explosions due to accidents or terrorist attacks. Close-in detonations lead to high intensity concentrated loads which can cause a premature brittle punching failure of the member. The assessment of such type of failure mode is challenging since the loading source varies its magnitude in space and time. This paper proposes an analytical method by which the occurrence of punching (or otherwise) is assessed by comparing the dynamic shear demand and capacity (supply). An exponentially decaying distribution of reflected overpressures on the RC surface is presented for this analysis. The punching shear demand is estimated from the pressure and inertial forces acting in the free-body diagram. The dynamic punching shear capacity is obtained using the Critical Shear Crack Theory with small slab deformations which are predicted from an equivalent single-degree-of-freedom model. The proposed approach takes into account the impulsive behaviour of the member leading to a higher punching capacity and provides better predictions than using existing formulae for punching which are based on tests with quasi-static loading and deformations. The proposed analytical equations are further supported by numerical explicit finite element models providing useful information of crack development, dynamic reactions and deflections. The application of the proposed method has been illustrated and validated by comparison with various tests with scale distances from 0.2 to 1.5 m/kg$^{1/3}$. A practical example is presented to illustrate the applicability of the proposed method.

1. Introduction

The increased threat of terrorist attacks as well as the occurrence of accidental explosions within or in close proximity to an engineering structure often leads the engineer to consider the actions of blast loading on the structure being designed. In the case of reinforced concrete (RC) structures, such loading can lead to various failure modes, including flexure, direct shear and punching shear. This paper is primarily concerned with the assessment of the latter form of structural failure. A number of situations can arise where blast loading can cause punching shear failure in a RC structure, viz. explosions occurring close to a blast and fire protection panel or an explosion close to a RC slab within a framed building, as shown in Fig. 1(a,b). For close-range blasts, a significant concentration of the load occurs adjacent to the blast point; the peak reflected pressures considered in this work varied between around 1 to 100 MPa. This load can result in the brittle development of a punching shear plug (Fig. 1(c)) as observed experimentally in [1–8] due to the impulsive behaviour described in Section 2.

Many researchers have studied experimentally the damage of RC slabs and panels of various dimensions when subjected to varying degrees of blast loading including Silva and Lu [3], Wang et al. [4,5], Zhao and Chen [7], Castedo et al. [8], Schenker et al. [9] and Fischer and Häring [10]. A number of researchers also studied the effect of strengthening RC slabs with novel polymeric composite materials (e.g. [1,2,11,12]). Empirically-based formulae have been developed such as Eq. (1) in [13,14] in an attempt to assess whether a RC element would be damaged or even breached when subjected to a blast load. The assessment is done on the basis of the element's thickness, h, and the blast loading parameters, viz. the mass of explosive material, W, and the stand-off distance between the explosive and the target, S. Walley proposed that no breaching would occur if:

$$\frac{h}{W^{\frac{1}{3}}} \geqslant 0.03\left(\frac{S}{W^{\frac{1}{3}}}\right)^{-0.62} \tag{1}$$

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[*] Corresponding author at: Faculty of Engineering and Physical Sciences, Civil Engineering C5, Guildford, Surrey GU2 7XH, UK.
E-mail address: j.sagaseta@surrey.ac.uk (J. Sagaseta).
[1] Currently at Tokyo Polytechnic University, Kanagawa, Japan.
[2] Currently at Skidmore, Owings & Merrill, Inc., London, UK.

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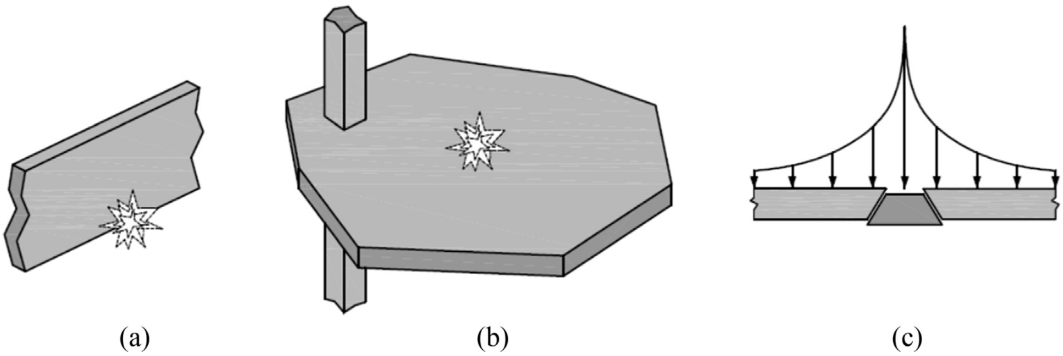

Fig. 1. Blast loading on (a) RC walls, (b) slabs and (c) pressure envelope near the blast and punching shear plug.

A number of difficulties can be associated with this expression, principally the fact that it is independent of the concrete compressive strength, which intuitively is a strength parameter. UFC 3-340-01 [15] proposes a similar relationship but accounting for concrete strength, such that no breach would occur if:

$$\frac{h}{S} \geqslant \frac{1}{a + b\Psi + c\Psi^2} \tag{2}$$

in which a, b and c are constants and Ψ is the spall parameter which for bare, non-contact hemispherical surface charges is given by

$$\Psi = \frac{S^{0.926} f_c^{0.266}}{W^{0.353}} \tag{3}$$

in which f_c is the concrete compressive strength in [MPa], S is the stand-off distance in [m] and W is in [kg]. Eqs. (2) and (3) were calibrated for tests with Ψ between 0.055 and 1.5. Eqs. (1) and (2) are applied in this work to estimate the level of damage and to compare it with the predictions from the proposed model which only looks at punching. Whilst simple, these formulae are purely empirical and do not distinguish between breach and punching. As highlighted in Silva and Lu [3] there is no analytical method of assessing the occurrence of punching in RC structures subjected to blast loading.

The aim of this paper is the development of an analytical approach based on punching under impulsive behaviour (refer to Section 2). The proposed method consists of three steps: (1) definition of blast loading parameters, (2) assessment of the maximum punching shear demand and (3) assessment of the dynamic punching capacity to compare it against the demand. An upper and lower bound estimates of the demand and capacity are obtained respectively during the blast load when punching can potentially occur. The proposed approach is validated against existing experimental data and it is also further supported by numerical simulations.

2. Punching shear under impulsive behaviour

This paper considers detonations with duration of a few milliseconds or less which can be considered of short duration compared to the occurrence of the natural (global) response of structural elements. Such loads result in an impulsive behaviour of the element with very small deflections at the time where the overpressure reaches its maximum value. In such cases, spall and breach of the panel can occur due to the compressive and tensile transmitted shock waves in the concrete or alternatively a punching shear plug could develop. The formation of a punching shear plug is primarily governed by the large punching shear forces (demand) that can be estimated using local models considering the overpressure and inertial forces acting in the element. On the other hand, the assessment of the punching shear capacity can be problematic in this case as most of punching formulae available correspond to quasi-static loading in which the level of strains in the concrete is not considered explicitly.

It is shown in this paper that strain-based punching capacity models such as the Critical Shear Crack Theory (CSCT) from Muttoni [16] are suitable to address cases of impulsive behaviour. According to the CSCT, the capacity is written as a function of the deformation of the slab (slab rotation outside the punching plug, θ, shown in Fig. 2a) which is an indirect measure of the strains in the concrete in relation with the opening of the critical shear crack. Fig. 2b shows the failure criterion in [16] in which the punching capacity increases for lower slab rotations. This relationship was derived analytically by means of a discrete crack approach with defined kinematics and constitutive equations for the stress transferred along the critical crack through aggregate interlocking and tensile stress in the concrete. The failure criterion for the concrete contribution can be adapted for high-strain rates as shown in Micallef et al. [17] and it can be added to the contribution of shear reinforcement [18] or steel fibres in the concrete [19] which also vary with θ. Given some load-rotation response for a particular slab system, the punching shear capacity, V_R, and the rotation at failure, θ_R, can be immediately established by the intersection of the two curves (Fig. 2b). This approach, which fundamentals were established in the 1980s by Muttoni [20], is the basis of *fib* Model Code 2010 [21] formulae for punching.

As shown in Fig. 2b, the CSCT predicts a higher punching capacity for cases with low rotations which is due to narrow cracks and the significant contribution of concrete in tension. The CSCT provides reasonable predictions in the region of low rotations as shown in slab tests subjected to localised impact loads with moderate strain-rates investigated in [17] as well as static load tests of slender slabs with very large flexural reinforcement ratios [16] and compact footings [22] where the shear deformation component is larger than the flexural one. Other approaches are available for estimating the capacity in cases of low deformations such as limit analysis [23], although the implementation of strain effects in the concrete strength can be cumbersome.

In order to derive an analytical approach in this work, the variation of the punching capacity during the load duration is neglected. A lower bound estimate of the capacity at the time of failure is obtained using the CSCT with a dynamic rotation estimated at the end of the applied load. The dynamic rotation is estimated using a simple SDOF model with transformation factors to take into account the impulsive response. For consistency, an upper bound estimate of the punching shear demand is estimated at failure; a free body diagram model is adopted for the local analysis of the shear forces. It is shown that for short load durations these assumptions can provide reasonable and systematic predictions of punching of existing test data.