International Journal of Impact Engineering 71 (2014) 17–33

Contents lists available at ScienceDirect

International Journal of Impact Engineering

journal homepage: www.elsevier.com/locate/ijimpeng

Review

Assessing punching shear failure in reinforced concrete flat slabs subjected to localised impact loading

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ARTICLE INFO

Article history:
Received 2 September 2013
Received in revised form
27 February 2014
Accepted 6 April 2014
Available online 19 April 2014

Keywords:
Punching shear
Flat slabs
Impact loading
Strain-rate effects
Critical shear crack theory

ABSTRACT

Reinforced concrete flat slab structures are used widely in construction projects due to their economic and functional advantages. Punching shear failure in such structures can have catastrophic effects in the case of, for example, multi-storey framed structures and the designer aims to ensure that ductile flexural deformation occurs before the brittle shear failure.

Shear mechanisms generally govern the behaviour of reinforced concrete structures subjected to localised impact loads. Existing experimental results investigating punching shear in flat slabs subjected to impact loading shows that when increasing the loading rate, the punching shear strength also increases whereas the deformation capacity reduces. This behaviour is due to a combination of inertial effects and material strain-rate effects which leads to a stiffer behaviour of the slab for higher loading rates. This can also lead to a change of mode of failure from flexural to pure punching shear with increasing loading rates. Current empirical formulae for punching shear are unable to predict this behaviour since the slab deformations are not considered for calculating the punching shear strength.

This paper presents an analytical model based on the Critical Shear Crack Theory which can be applied to flat slabs subjected to impact loading. This model is particularly useful for cases such as progressive collapse analysis and flat slab-column connections subjected to an impulsive axial load in the column. The novelty of the approach is that it considers (a) the dynamic punching shear capacity and (b) the dynamic shear demand, both in terms of the slab deformation (slab rotation). The model considers inertial effects and material strain-rate effects although it is shown that the former has a more significant effect. Moreover, the model allows a further physical understanding of the phenomena and it can be applied to different cases (slabs with and without transverse reinforcement) showing a good correlation with experimental data.

1. Introduction

1.1. High-rate loading

The design of most reinforced concrete (RC) structures is typically governed by ultimate limit state performance of the various structural elements when subjected to static loading, e.g. dead (or permanent) loads and live (or imposed or variable) loads. Whilst the former are typically static in nature (e.g. structure's self-weight, finishes etc.), the magnitude of live loading tends to be variable with time (e.g. pedestrian or vehicular traffic loading). However, in most cases, such loadings can be idealised as quasi-static, since the rate at which this loading is applied, typically described by the strain-rate, $\dot{\varepsilon}$, is of a very small magnitude.

Fig. 1 gives typical ranges of strain-rates for different loading sources.

Dynamic loads are often also idealised as being quasi-static or replaced by equivalent static loadings but in the case of extreme events, such as blast or impact loading, such simplifications could be inadequate and further consideration is necessary [2]. Reliable structural modelling is essential to accurately predict the response and damage in structures subjected to loads at high strain-rates. The effects of strain-rate effects can be considered on two levels, viz. the effects on the material properties of the structure's constituents and the effects on the response of the structure itself.

1.2. Effect of strain-rate on material properties

The effect of strain-rate on the mechanical properties of most engineering materials is well-known. This includes the

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http://dx.doi.org/10.1016/j.ijimpeng.2014.04.003

Nomenclature

Latin lower case

a	penetration constant, [T^{-2}]
b	penetration constant, [L^{-2}]
b_0	punching control perimeter, [L]
c_1	tension softening constant, [−]
c_2	tension softening constant, [−]
c_{s0}	slab initial damping co-efficient, [$M\ T^{-1}$]
c_s	slab damping co-efficient, [$M\ T^{-1}$]
d_g	concrete maximum aggregate size, [L]
d_{g0}	reference concrete aggregate size, [L]
d_v	shear-resisting slab effective depth, [L]
d	slab effective depth, [L]
f_c	concrete compressive strength, [$M\ L^{-1}\ T^{-2}$]
f_{c0}	reference concrete compressive strength, [$M\ L^{-1}\ T^{-2}$]
f_{ct}	concrete tensile strength, [$M\ L^{-1}\ T^{-2}$]
f_y	steel reinforcement yield stress, [$M\ L^{-1}\ T^{-2}$]
g	acceleration due to gravity, [$L\ T^{-2}$]
h_i	drop height of impactor, [L]
h_s	slab thickness, [L]
k_c	contact stiffness, [$M\ T^{-2}$]
k_{s0}	slab initial stiffness, [$M\ T^{-2}$]
k_s	slab stiffness, [$M\ T^{-2}$]
m_i	mass of impactor, [M]
m_{s0}	slab initial mass, [M]
m_s	slab mass, [M]
r_c	column radius, [L]
r_s	position of zero bending moment with respect to support axis, [L]
r_{s0}	initial position of zero bending moment during contact time, [L]
t	time, [T]
t_c	contact time, [T]
t_E	time to peak response, [T]
$u_i(t)$	impactor displacement, [L]
$\dot{u}_i(t)$	impactor velocity, [$L\ T^{-1}$]
$\ddot{u}_i(t)$	impactor acceleration, [$L\ T^{-2}$]
$u_s(t)$	slab displacement, [L]
$\dot{u}_s(t)$	slab velocity, [$L\ T^{-1}$]
$\ddot{u}_s(t)$	slab acceleration, [$L\ T^{-2}$]
v_c	concrete shear wave velocity, [$L\ T^{-1}$]
w	crack width, [L]
w_c	maximum crack width, [L]

Latin upper case

$\overline{A}_x$	projected contact areas in the X direction for an unit crack area, [−]
$\overline{A}_y$	projected contact areas in the Y direction for an unit crack area, [−]
A	impactor section pressure, [$M\ L^{-1}\ T^{-2}$]
E_c	concrete elastic modulus, [$M\ L^{-1}\ T^{-2}$]
E_s	steel reinforcement elastic modulus, [$M\ L^{-1}\ T^{-2}$]
G_c	concrete shear modulus, [$M\ L^{-1}\ T^{-2}$]
G_F	fracture energy, [$M\ T^{-2}$]
G_{F0}	reference fracture energy, [$M\ T^{-2}$]
K	material constant, [$M^{-1}\ L^2\ T^2$]
L_{eff}	slab effective span, [L]
M_{Rd}	unit slab flexural capacity, [$M\ L\ T^{-2}$]
M_{sd}	unit slab bending moment, [$M\ L\ T^{-2}$]
N	crack normal force component, [$M\ L\ T^{-2}$]
$P(t)$	contact force, [$M\ L\ T^{-2}$]
$\dot{P}$	loading rate, [$M\ L\ T^{-3}$]
P'	section limiting load, [$M\ L\ T^{-2}$]
R_i	impactor radius, [L]
S	crack shear force component, [$M\ L\ T^{-2}$]
V	penetration velocity, [$L\ T^{-1}$]
V'	velocity factor, [−]
V_0	impactor initial velocity, [$L\ T^{-1}$]
V^*	velocity constant, [$L\ T^{-1}$]
V_d	shear force, [$M\ L\ T^{-2}$]
V_R	punching shear strength, [$M\ L\ T^{-2}$]
X	penetration depth, [L]
$\ddot{X}$	penetration acceleration, [$L\ T^{-2}$]

Greek lower case

β	shear modulus retention factor, [−]
γ	concrete dilatation angle, [−]
δ	crack separation, [L]
$\dot{\varepsilon}$	strain-rate, [T^{-1}]
μ	co-efficient of friction, [−]
ν	Poisson's ratio, [−]
ρ	flexural reinforcement ratio, [−]
ρ_c	concrete density, [$M\ L^{-3}$]
ρ_v	shear reinforcement ratio, [-]
σ_{ca}	concrete aggregate interlock normal stress, [$M\ L^{-1}\ T^{-2}$]
σ_{ct}	concrete tensile stress, [$M\ L^{-1}\ T^{-2}$]
σ_p	cement paste plasticisation stress, [$M\ L^{-1}\ T^{-2}$]
τ_{ca}	concrete aggregate interlock shear stress, [$M\ L^{-1}\ T^{-2}$]
$\varphi(x)$	slab deformed configuration shape function, [−]
ϕ	reinforcement bar diameter, [L]
ψ	slab rotation, [−]
ψ_R	slab rotation at failure, [−]

constituents of RC structures, namely the concrete and the steel reinforcement.

1.2.1. Concrete properties

It has been shown by many researchers (e.g. Refs. [3–11]) that the tensile and compressive strengths of concrete both increase with loading rate. A very comprehensive review of experimental data in this respect has been carried out by Cotsovos and Pavlović [12].

The 1990 and 2010 Model Codes [1,13,14] provide relationships which give the increase in strength and modulus with strain-rate. These relationships are valid for strain rates up to 300/s covering low to moderate impacts. The increases in compressive (f_c) and tensile (f_t) strengths are given by (1) and (2) respectively as:

$$\frac{f_{c,\mathrm{dynamic}}}{f_{c,\mathrm{static}}} = \begin{cases} \left(\dfrac{\dot{\varepsilon}}{30\times10^{-6}}\right)^{0.014}, & \dot{\varepsilon} \le 30/s \\ 0.012\left(\dfrac{\dot{\varepsilon}}{30\times10^{-6}}\right)^{\frac{1}{3}}, & 30/s \le \dot{\varepsilon} \le 300/s \end{cases} \tag{1}$$