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Numerical strategies for damage assessment of reinforced concrete block walls subjected to blast risk

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ABSTRACT

Computational tools and numerical strategies for the determination of the response of masonry walls under blast overpressure often rely on oversimplifying and conservative assumptions, which, although justifiable for design purposes, are not as warranted when fragility analysis and risk assessment are the objectives. In addition, due to the composite nature of reinforced masonry construction, the evaluation of multivariate fragility functions may likely require significant computational effort, owing to the multiplicity of variables describing the constituent materials and their associated uncertainty. The problem is further compounded by the effects of the high strain rates typically induced by blast loading, which make the understanding of masonry behaviour even more challenging; although efforts are being made in order to account for strain rate effects at the macro-scale, no well established models are available for reinforced masonry walls. Therefore, in order to perform accurate yet expedient fragility analyses that can effectively capture rate dependent phenomena, a dynamic model based on single-degree-of-freedom (SDOF) approach is developed. The SDOF model accounts for the nonlinear stress–strain behaviour obtained from standard prism tests and integrates strain rate dependent formulations provided in the open literature. The model predictions are corroborated using data—including pressure and displacement histories—from field testing of six scaled concrete block walls subjected to the detonation of live explosives. Within the scope of the current study, the proposed model is found to be a reasonable trade-off between computational efficiency and numerical accuracy and is an improvement upon a basic SDOF approach, which is typically based on the fixed dynamic increase factors recommended by modern design standards and technical manuals for blast protection. The results presented in this study are expected to contribute to the ongoing development of a comprehensive framework for the probabilistic risk assessment of structures subjected to explosive loading.

1. Introduction

A rigorous approach to the development of blast risk mitigation strategies requires the probabilistic assessment of risk associated with a range of plausible blast events and cost-benefit analysis of potential measures for risk reduction [1]. One of the fundamental steps leading to the quantification of risk is the evaluation of structural fragility, which provides crucial information by mapping the probability of failure across the space of load variables most significant to the structural response, e.g. the peak pressure and specific impulse delivered by the blast [2,3]. However, depending on the number of variables being investigated and the complexity of the blast scenario, the computation of representative fragility curves may require Monte Carlo simulations [4] involving a large number of computer runs for the determination of the structural response. Hence, the accuracy and computational efficiency of the adopted numerical models become of great interest as the number of variates in any given simulation increases. When the problem at hand involves concrete masonry walls subjected to explosive loading, the evaluation of structural fragility may become exceedingly costly, owing to the large number of variables governing wall behaviour, their large variability [5], and the complex interactions between the constituent materials [6]. As such, a brief review of the strategies that may lead to an effective evaluation of the response of structural masonry is included in the following section, as it is relevant to the current discussion.

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Nomenclature

A_s	area of steel reinforcement (mm^2)
b	wall cross-section net width (mm)
b_i	width of the i-th fiber (mm)
BRASS	Blast Risk Analysis and Simulation Software
c	depth of neutral axis (mm)
$\dot{c}$	rate of change of neutral axis depth (mm/ms)
DIF	dynamic increase factor
DIF_E	Ngo et al. [53] DIF associated with the elastic moduli
DIF_f	Ngo et al. [53] DIF associated with the compressive strength
DIF_ε	Ngo et al. [53] DIF associated with the strain at peak stress
DM1	mid-span displacement sensor No. 1
DM2	quarter-span displacement sensor No. 2
DM3	quarter-span displacement sensor No. 3
d	wall cross-section effective depth (mm)
E_o	tangent elastic modulus at zero strain in masonry (MPa)
E_s	secant elastic modulus at peak stress in masonry (MPa)
F	forcing function (N)
F_i	forcing function at the i-th time step (N)
$\dot{F}$	rate of change of the forcing function (N/ms)
$\dot{F}_i$	rate of change of the forcing function at the i-th time step (N/ms)
FSIF	flexural strength increase factor
f_m	stress in masonry (MPa)
$\bar{f}_m$	normalized stress in masonry
f'_m	average compressive strength of masonry prism (MPa)
f_{mi}	i-th stress measurement in masonry (MPa)
$\bar{f}_{mi}$	i-th normalized stress
$\bar{f}_{mx}$	normalized stress value associated with the strain $\bar{\varepsilon}_{mx}$ (typically, $\bar{f}_{mx} = 0.2$)
f_s	stress in steel reinforcement (MPa)
f_t	masonry flexural tensile strength for stresses orthogonal to the bed joints (MPa)
h	test wall thickness (mm)
H_P	thickness of masonry prism (mm)
i	dummy variable (counter)
J_{AV}	weighted average moment of inertia of the wall cross-section (mm^4)
J_{cr}	moment of inertia of the cracked wall cross-section (mm^4)
J_g	moment of inertia of the wall gross cross-section (mm^4)
j	dummy variable (counter)
k	wall tangent stiffness for SDOF analysis (N/mm)
k_{AV}	stiffness based on weighted average cross-sectional inertia (N/mm)
k_i	wall tangent stiffness at the i-th time step (N/mm)
K_L	load factor for SDOF analysis
K_{LM}	load-mass factor for SDOF analysis
$K_{LM\text{-}i}$	i-th load-mass factor for SDOF analysis
L	length of the test wall sides (mm)
L_P	height of masonry prism (mm)
M	bending moment (kN m)
M_{ij}	bending moment at $t = t_i$ and at $z = z_j$ (kN m)
M_j	bending moment at $z = z_j$ (kN m)
M_R	moment resistance (kN m)
m	wall mass (kg)
N_f	number of fibers parallel to the direction of the cross-section width
N_s	number of cross-sections along the wall span
n	fitting factor of the ascending branch of the masonry stress-strain relationship in compression
P	blast overpressure (kPa)
PM3	reflected pressure gauge No. 3
PM4	reflected pressure gauge No. 4
PM5	reflected pressure gauge No. 5
R	resistance function for SDOF analysis (N)
R_o	least squares approximation of BRASS output resistance function (N)
R_{oi}	R_o value at $t = t_i$ (N)
R_i	resistance function at the i-th time step (N)
R_{i+1}	resistance function at the $(i+1)$-th time step (N)
R_m	peak value of the resistance function (N)
R^T	true resistance function from load-deflection analysis (N)
R_i^T	true resistance function at the i-th time step (N)
r	dummy variable
SDOF	single-degree-of-freedom
S	sum of squared residuals
s	dummy variable
T	fundamental period of vibration (ms)
t	time (ms)
t_o	time subsequent to both the end of the forced vibration phase and the attainment of peak resistance (ms)
t_i	i-th time step (ms)
t_{i+1}	$(i+1)$-th time step (ms)
t_m	time of maximum deflection at mid-span (ms)
t_r	time when R_m is first attained (ms)
U	unbalanced force (N)
U_i	unbalanced force value at the i-th time step (N)
V	dynamic reaction (N)
v	wall deflection curve (mm)
v_j	wall deflection at $z = z_j$ (mm)
w_i	i-th weight for numerical integration (Simpson's 1/3 rule)
y	distance from the side of the wall cross-section directly exposed to the blast (mm)
y_i	y-coordinate of the i-th fiber (mm)
z	distance from a wall support (mm)
z_j	j-th distance from a wall support (mm)
δ	mid-span deflection (mm)
δ_i	mid-span deflection at the i-th time step (mm)
δ_{i+1}	mid-span deflection at the $(i+1)$-th time step (mm)
$\dot{\delta}$	mid-span velocity (mm/ms)
$\dot{\delta}_i$	mid-span velocity at the i-th time step (mm/ms)
$\ddot{\delta}$	mid-span acceleration (mm/ms^2)
$\ddot{\delta}_{i+1}$	mid-span acceleration at the $(i+1)$-th time step (mm/ms^2)
δ_o	mid-span deflection at t_o (mm)
$\dot{\delta}_o$	mid-span velocity at t_o (mm/ms)
δ_m	mid-span maximum deflection (mm)
$\dot{\delta}_m$	velocity at mid-span maximum deflection (mm/ms)
κ	curvature (1/mm)
κ_j	curvature at $z = z_j$ (1/mm)
$\dot{\kappa}$	curvature rate (1/mm ms)
$\dot{\kappa}_{ij}$	curvature rate at $t = t_i$ and at $z = z_j$ (1/mm ms)
$\dot{\kappa}_{AV}$	average curvature rate (1/mm ms)
λ	fitting factor of the descending branch of the masonry stress-strain relationship in compression
λ_o	value attained by λ when $\varepsilon_m = 2\varepsilon'_m$
λ_i	i-th λ value based on i-th test data point
λ_L	value asymptotically approached by λ for large strains
λ_x	λ value associated with $\bar{\varepsilon}_{mx}$ and $\bar{f}_{mx}$
$\bar{\varepsilon}_L$	normalized strain value related to the vertical asymptote of the λ-function
ε_m	strain in masonry
$\bar{\varepsilon}_m$	normalized strain measurement
$\dot{\varepsilon}_m$	strain rate in masonry (1/s)
ε'_m	average masonry strain at peak stress in compression
ε_{mi}	i-th strain measurement in masonry