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DEPENDENCE OF STRENGTH ENHACEMENT ON SHOCK FRONT OVERPRESSURE: THE CASE OF RC STRUCTURES

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Annotation. The paper considers problems related to the assessment of the effect of loading rate on mechanical properties of concrete and reinforcing steel. The attention is focused on the evaluation of varying straining rate of RC structure subjected to explosive loading. The key problem considered in the paper is the derivation of the relation between the rate of pressure increase and incident overpressure. The paper considers approaches to modelling the influence of straining rate on mechanical properties of concrete and reinforcing steel. The main conclusion following from the paper is that the deterministic models used for the assessment of effect of straining rate on the mechanical properties of concrete and reinforcing steel and models used for modelling of incident overpressure are fairly imprecise and require for the stochastic modelling of this phenomena.

Keywords: loading rate, strain rate, incident overpressure, shock front.

Introduction

A surface explosion may result in severe damage even collapse of nearby structures. As a consequence, it always causes economic loss, usually loss of life and unavoidable psychological impact to the general public. To reduce the consequences, clear understanding of the structural response and damage characteristics to explosive loads is essential.

The ability of reinforced concrete of RC to absorb energy under dynamic transient nonlinear conditions has led to its utilisation for several classes of important structures, e.g. nuclear containment vessels, power plant structures, protective barriers, etc. which may be subjected to impact or explosive loading. The low probability of occurrence of these loads necessitates a limit state approach to design in which irreversible structural deformation and material damage is acceptable provided that overall structural integrity is maintained (Vaidogas 2005a, 2005b). The numerical simulation of such structural responses therefore requires the simultaneous consideration of both dynamic material properties and geometrical nonlinearities.

The rate sensitivity of concrete plays a considerable role in its dynamic load-carrying capacity. By increasing either stress or strain loading rates, the strength of concrete is significantly increased.

Reflection of shock front as a source of high-rate loading

It is well known that properties of a material are very much dependent on straining rate, to which these materials are subjected. The higher straining rates are usually achieved during explosions and impacts (CEB-FIP 1988: 3.6). Loads imposed by such loadings are called impulsive once. In the case of an explosive loading the response of RC structure will occur in so short a time that no viscous damping can be invoked. For a structure subjected to an impulsive loading, the first displacement peak will be the most severe. Subsequent cycles will decrease significantly in magnitude and the oscillation will die down rapidly. Moreover, under severe blast loading, the structure is likely to undergo excessive permanent deformation during its first displacement, and its very unlikely for a structure to fail during its second displacement peak. Therefore, in most cases, only first displacement peak is considered in analyzing structural response to impulsive loading (Low & Hao 2001; Zhou *et al.* 2008).

A typical explosive loading generated by a distant explosion is characterised by its peak reflected pressure $P_{\mathrm{r,max}}$ and positive phase duration t_+, whereas the negative phase is usually ignored in the explosive damage assessment.

During the explosive loading the structure will be subjected to varying straining rate. The strain rate is

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usually assumed constant for the duration of the analysis and the assumption of constant strain rate gives good results (Krauthammer *et al.* 1994). This assumption is valid with a high probability for the rise time t_{rise} (Fig. 1). The rise time t_{rise} can be roughly assumed as maximum 25% of the positive duration time t_+ (Zhou & Hao 2008). For instance, Low & Hao assumed in their calculations that $t_{\text{rise}} = 0{,}1\text{ms}$. However, for TNT explosions, a more accurate modelling exists and allow to assess t_{rise} of the incident shock front from the following relation:

$$t_{\text{rise}} = 0{,}0019\left(\frac{R}{Q^{1/3}}\right)^{1{,}30}. \tag{1}$$

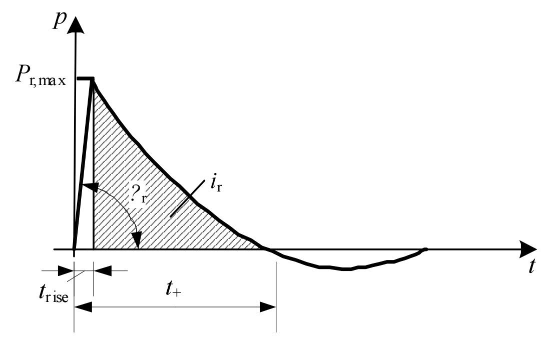

Fig. 1. Pressure signal of the reflected wave resulting from a distant explosion (t_{rise} = rise time)

Here R is the distance from the charge centre; Q is the TNT charge weight.

The pressure is assumed to increase linearly (Fig. 1) to its peak value with a rising time t_{rise}. The rising time t_{rise} is proportional to the scaled distance regardless of charge weights.

With the rise time t_{rise} and the incident overpressure $P_{\text{i,max}}$, the rate of pressure increase is calculated by the simple relation:

$$\dot{p}_{\text{i}} = \frac{P_{\text{i,max}}}{t_{\text{rise}}}. \tag{2}$$

The blast loading on the structure occurs as a reflection on the incident blast wave. The overpressure on the face of the structure rises to $P_{\text{r,max}}$. And then decreases to the ambient pressure after some time t_+. In the case of a distant explosion the pressure signal of the reflected shock front is described by the relation:

$$P_{\text{r}}(t) = P_{\text{max,r}}\exp\{-\alpha t\} = P_{\text{max,r}}\exp\left\{-\frac{2t}{t_{+\text{r}}}t\right\}. \tag{3}$$

An illustration of this pressure signal is given in Fig. 1.

As the blast loading on structure is defined by the reflected pressure signal, the loading rate determining mechanical properties of concrete and reinforcing steel will depend on the rate of increase of pressure of the reflected signal (i.e., $\text{tg}\alpha_{\text{r}}$, see Fig. 1). One can roughly estimate the reflected specific impulse, by assuming similarity between the time histories of incident and reflected waves. This assumption gives the following relation (Baker *et al.* 1983):

$$\frac{P_{\text{r,max}}}{P_{\text{i,max}}} = \frac{i_{\text{r}}}{i_{\text{i}}}. \tag{4}$$

The similarity of pressure signals allows to make also an assumption about the ratio of the rising times of the incident and reflected shock fronts:

$$\frac{P_{\text{r,max}}}{P_{\text{i,max}}} = \frac{t_{\text{r,rise}}}{t_{\text{i,rise}}}. \tag{5}$$

The later assumption leads to the result that the rate of pressure increase during the rising time $\dot{p}$ can be estimated by the parameters of the pressure signal of the incident shock front:

$$\dot{p} = \text{tg}\alpha_{\text{r}} = \frac{P_{\text{i,max}}}{t_{\text{rise}}}. \tag{6}$$

Similarly to the calculation of t_{rise} by Eq (1), the incident overpressure $P_{\text{i,max}}$ can be calculated as a function of the distance from the charge centre R and the TNT charge weight Q (Wu & Hao 2005):

$$P_{\text{i,max}} = \begin{cases} 1{,}059\left(\dfrac{R}{Q^{1/3}}\right)^{-2{,}56} - 0{,}051 \; \textit{if} \; 0{,}1 \le \dfrac{R}{Q^{1/3}} \le 1, \\ 1{,}008\left(\dfrac{R}{Q^{1/3}}\right)^{-2{,}01} \quad \textit{if} \; 1 < \dfrac{R}{Q^{1/3}} \le 10. \end{cases} \tag{7}$$

As the empirical relations (1) and (7) depend on the scaled distance $R/Q^{1/3}$, the rate of pressure increase $\dot{p}$ can be expressed as a function of the overpressure $P_{\text{i,max}}$ alone:

$$\dot{p} = \begin{cases} 511{,}2P_{\text{i,max}}\left(P_{\text{i,max}} + 0{,}051\right)^{0{,}508}; \; 0{,}1 \le \dfrac{R}{Q^{1/3}} \le 1, \\ 523{,}6P_{\text{i,max}}^{1{,}647}; \; 1 < \dfrac{R}{Q^{1/3}} \le 10. \end{cases} \tag{8}$$

Figure 2 shows an illustration of the dependence $\dot{p}$ versus $P_{\text{i,max}}$. Considerations expressed Eqs (1) to (8) lead to two simple conclusions: firstly, the loading rate $\dot{p}$ can be predicted with the overpressure of the incident and not the reflected shock front, $P_{\text{i,max}}$; secondly, the loading rate $\dot{p}$ depends on $P_{\text{i,max}}$ non-linearly and this non-linearity relatively strong.

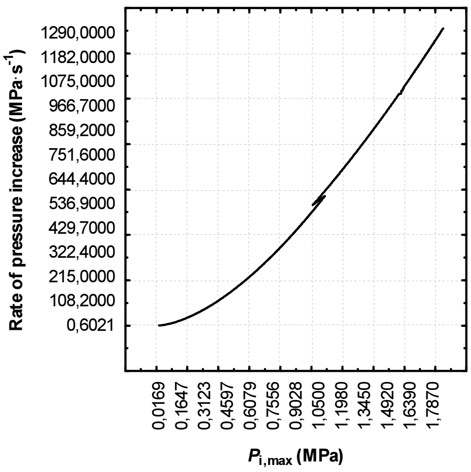

Fig. 2. Rate of pressure increase p and overpressure $P_{\mathrm{i,max}}$ relation

The above conclusions allow to make the further statement, namely, the non-linear relationship will exist also between the overpressure $P_{\mathrm{i,max}}$ and the dynamic mechanical properties of steel and concrete. Even in the case when the relation between p and the mechanical properties is linear.

Deterministic modelling of the influence of strain rate on concrete properties

It is well-known that the strength of concrete is considerably affected by the rate of application of the load: the lower the rate of loading, the lower the apparent strength. This is probably due to the increase in strain with time owing to creep and micro-cracking. The normal rate of static loading for the standard cylinder test is approx 0,2…1 MPa/s (Mirza *et al.* 1979; CEB-FIP 1988). This corresponds to the static strain-rate of approximately $30 \cdot 10^{-6}$ s^{-1}. Compared with the rate of loading, at 7 kPa/s (1 psi/s) reduces the apparent strength of concrete by approx 12% whereas loading at 7000 kPa/s (1000 psi/s) increases the strength by approx 12%. Concrete is capable to withstand stresses only up to 70% – 75% of the strength under loads applied at 0,2 MPa/s (35 psi/s) (Mirza *et al.* 1979; Grote *et al.* 2001; Park *et al.* 2001).

A popular strain-rate dependent model of concrete mechanical properties was introduced by CEB-FIP (1988). This model was widely used by various authors for dynamic analysis of concrete structures (Low & Hao 2001, 2002). The model recommended by CEB-FIP consists of enhancement factors which can be calculated for given stress-rate $\dot{\sigma}$ or strain-rate $\dot{\varepsilon}$.

Table. Enhancement factors for properties of concrete presented in CEB-FIP model [1988]

Properties of concrete	Enhancement factor	Explanations
$f_{\mathrm{c,d}} / f_{\mathrm{c,st}}$	$(\dot{\varepsilon}/\varepsilon_0)^{1{,}026\alpha}$ for $\dot{\varepsilon} \le 30\ \mathrm{s}^{-1}$ $\gamma\dot{\varepsilon}^{1/3}$ for $\dot{\varepsilon} > 30\ \mathrm{s}^{-1}$	$\varepsilon_0 = 30 \cdot 10^{-6}$ s^{-1} $\alpha = 1/(5+3f_{\mathrm{c,st}}/4)$ $\log\gamma = 6{,}156\alpha - 0{,}492$
$E_{\mathrm{c,d}} / E_{\mathrm{c,st}}$	$(\dot{\varepsilon}/\varepsilon_0)^{0{,}026}$	$\varepsilon_0 = 30 \cdot 10^{-6}$ s^{-1}
$\varepsilon_{\mathrm{u,d}} / \varepsilon_{\mathrm{u,st}}$	$(\dot{\varepsilon}/\varepsilon_0)^{0{,}02}$	$\varepsilon_0 = 30 \cdot 10^{-6}$ s^{-1}

Some elements of CEB-FIP model expressed through the strain-rate are summarised in Table.

Unfortunately, the CEB-FIP model is purely deterministic. It is unclear what degree of uncertainty is related to the predictions of concrete dynamic properties yielded by this model. The only attempt to quantify this uncertainty known for us is the theoretical investigation of variability of these properties carried out by Mihashi & Wittmann (1980). Another characteristic feature of concrete behaviour under dynamic loads, which follows from the CEB-FIP model is that the enhancement factors presented in Table 1 are relatively insensitive to the changes of the strain rate $\dot{\varepsilon}$. A simple illustration of this fact is presented in Figures 3...5.

The evaluation of dynamic concrete material properties presented in CEB-FIP (1988) assesses the class of concrete through the coefficient α presented in Table. Liu & Owen (1986) introduced a rate sensitive function $\Phi(\dot{\varepsilon})$ for concrete in which different concrete static strengths are taken into account:

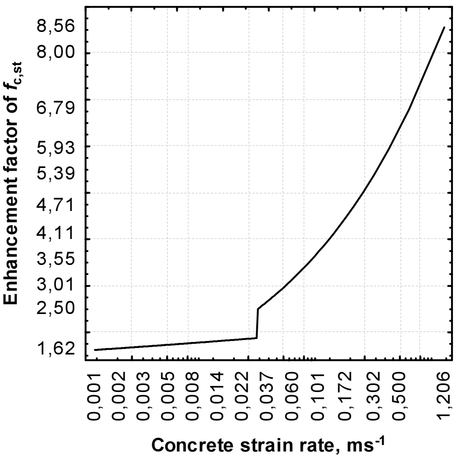

Fig. 3. Enhancement factor for static compressive strength of concrete $f_{\mathrm{c,st}}$ presented in CEB-FIP model [1988] for different concrete strain rates $\dot{\varepsilon}$ ms^{-1}

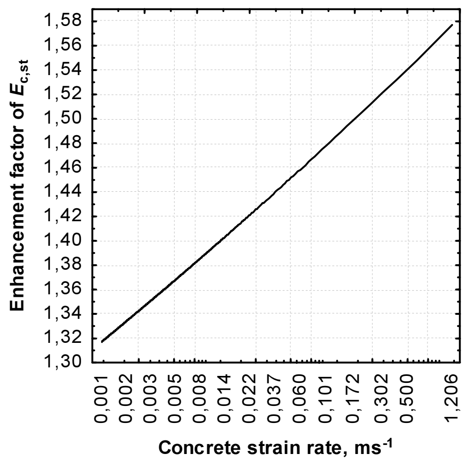

Fig. 4. Enhancement factor for static deformation modulus of concrete $E_{c,st}$ presented in CEB-FIP model [1988] for different concrete strain rates $\dot{\varepsilon}$ ms^{-1}

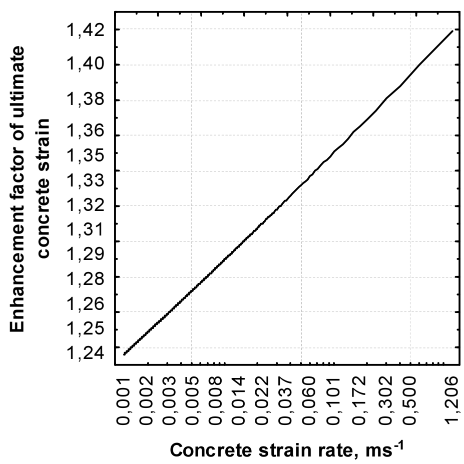

Fig. 5. Enhancement factor for static ultimate strain of concrete $\varepsilon_{u,st}$ presented in CEB-FIP model [1988] for different concrete strain rates $\dot{\varepsilon}$ ms^{-1}

The evaluation of dynamic concrete material properties presented in CEB-FIP (1988) assesses the class of concrete through the coefficient α presented in Table. Liu & Owen (1986) introduced a rate sensitive function $\Phi(\dot{\varepsilon})$ for concrete in which different concrete static strengths are taken into account:

$$\Phi(\dot{\varepsilon}) = \frac{f_{c,d}}{f_{c,s}} = \alpha \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_s} \right)^{\alpha_1} + 1, \tag{9}$$

where material parameters α and α_1 are material dependent. For a concrete with static strength $f_{c,s}$ lower than 44 MPa, $\alpha = 0{,}02789$; $\alpha_1 = 0{,}330123$ and for $f_{c,s}$ equal to 60,5 MPa, $\alpha = 0{,}011768$; $\alpha_1 = 0{,}38533$; $\dot{\varepsilon}_s = 10^{-5}$ s^{-1} is the static value of the strain rate (i.e. the strain rate value below which no rate sensitivity effects are evident).

Deterministic modelling the influence of strain rate on steel properties

Similarly to the concrete, the apparent yield strength of a steel increases as the strain-rate or the rate of loading increases. Since mill tests on mill specimens are generally carried out at much greater strain-rates (approx 0,104% s^{-1}) than encountered in structures subjected to static loads (Yang & Lok 2007).

The dynamic enhancement factor used for the calculation of the dynamic strength of steel was suggested by Liu and Owen (1986):

$$\Phi(\dot{\varepsilon}) = \frac{f_{s,d}}{f_{s,s}} = \lambda \mathrm{Log}_{10} \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_s} \right) + 1, \tag{10}$$

where the static value of strain rate $\dot{\varepsilon}_s$ is obtained to be 10^{-2} s^{-1}; the parameter λ is 0,03 within the range of fit 2–3 per cent strain.

Conclusions

1. The incident overpressure of explosion shock front and the duration of pressure increase depends on two parameter: the distance between the centre of explosion and subjected structure R and the equivalent mass of explosives Q.

2. The rate of pressure increase can be linearly expressed through the incident overpressure using two simple assumptions: the similarity between reflected $P_{r,max}$ and incident $P_{i,max}$ overpressures and reflected i_r and incident i_i impulses; and the similarity between reflected and incident overpressures and reflected and incident rise time t_{rise}.

3. Mean strain rates of concrete and reinforcing steel non-linearly depend on the rate of loading. Dynamic mechanical properties of concrete (dynamic strength of compression, dynamic Young modulus and dynamic ultimate deformation) non-linearly depend on the strain rate and loading rate.

4. The uncertainties in mathematical model of overpressure and time dependence and the uncertainties in the deterministic mechanical models used for the assessment of strains and strain rates of concrete and reinforcing steel require stochastic modelling of the enhancement factor for the evaluation of dynamic material properties.

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GELŽBETONINIŲ KONSTRUKCIJŲ SLĖGIMO BANGOS VIRŠSLĖGIO IR STIPRIO DIDĖJIMO PRIKLAUSOMYBĖ

V. Juocevičius

Santrauka

Straipsnyje analizuojama apkrovimo greičio betono ir armatūros mechaninėms fizikinėms savybėms įtaka. Daugiausia dėmesio skiriama gelžbetoninei konstrukcijai, veikiamai sprogimo bangos sukelto slėgio, betono ir armatūros, deformacijų, greičiui nustatyti. Straipsnyje pasiūlyta apkrovimo greičio priklausomybė nuo krentančios sprogimo bangos viršslėgio. Analizuojami deformacijų greičio įtakos betono ir armatūros mechaninėms ir fizikinėms savybėms vertinimo metodai, deterministinių metodų, naudojamų deformacijų greičio įtakai vertinti, betono, armatūros dinaminių ir mechaninių savybių netikslumai. Siūloma konstrukcijų, veikiamų sprogimo apkrovos, dinaminėms mechaninėms fizikinėms charakteristikoms nustatyti naudoti tikimybinį modeliavimą įvertinant atsitiktinius ir episteminius neapibrėžtumus.

Reikšminiai žodžiai: apkrovimo greitis, deformacijų greitis, atspindėtoji banga, viršslėgis.