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Objectives

The focus of this project is to support CEWES in the study of the prediction of degree of degradation and residual life capacity of structures which have been damaged either by single catastrophic events such as explosions or fire, or repeated (episodic and/or continuous) events such as earthquakes, tidal action, and wind gusts among others. This effort will combine existing analysis methods with enhanced data exchange, high performance computing, and advanced visualization methods within a single environment.

Approach

The approach taken in this effort consisted of three primary phases. In the first, the CAU research team, led by O. Olatidoye in close collaboration with the technical point of contact (TPOC) R. Namburu, surveyed the existing (public domain) state-of-art in modeling of structures exposed to blast loading. This literature search included methods to represent blast loading in a semi-empirical manner, analysis techniques used to predict the effects of such loading, as well as the damage assessment criteria applied to such structures. This article describes the efforts completed under the first phase.

The literature search focused primarily on more recent articles dealing with analysis and prediction of blast effects on buildings as a result of terrorist acts. Much work in the area

of blast analysis has been done prior to these articles, however, a majority of this information is still restricted due to its military significance. In addition to actual blast loading due to explosions, a small selection of articles related to impact loading (as in the case of earthquakes) were also reviewed. The search was conducted in two broad thrusts. First, the articles on blast load modeling were identified. While there were several hundred relevant articles on this subject, the actual mathematical formulation used to describe the transient pressure loading of a building in the vicinity of an external explosion did not vary a great deal. The second thrust was in identifying damage assessment methods used to characterize failure and damage in the context of blast loaded structures. The majority of articles reviewed used some combination of material constitutive relationships and bounds on the static or dynamic structural deformation to identify and in some cases quantify damage. For the most part, there was very little distinction between degraded load capacity, impending failure, and damage.

Blast Load Modeling

In a survey of the state-of-art in blast effects, Beshara [6,7] has identified various contributions to the understanding and modeling of the blast loading on buildings [Beshara 94a]. The shock of the blast wave is generated when the surrounding atmosphere is subject to a extreme compressive pulse radiating outward from the center of explosion. This wave traveling at hyper-velocities represents the shock front consisting of highly compressed air at overpressures much greater than in the region behind it. This peak overpressure drops rapidly as the shock propagates outward [44]. Behind the shock, the pressure of the air can drop below ambient, creating a suction effect. The shock wave traveling outwards from the source, is reflected when it meets an object with higher density than the normal atmosphere, such as the ground. The reflected wave travels back towards the origin. The overpressure of the reflected wave may exceed the overpressure of the incident wave, and due to its higher velocity, will eventually catch up with the incident wave. The resulting wave travels horizontally forming a single vertical shock front. This vertical front (known as the *Mach front* or *Mach stem*) and the incident and reflected waves meet at some distance above the ground at a point known as the *triple point* [3,4,9,1,22,23,27,32,38,44]. The presence of a limiting ground-zero distance

necessary for a Mach stem to form has been pointed out in [17]. The authors provide correlation with experimental evidence done by Ayvazyan [2].

Blast Wave Profile

While the source and physical nature of the explosion causing the shock wave can vary greatly, the pressure-time profile of a typical blast wave can be accurately represented [1, 33, 35-37]. For any time *arrival time* t_a ($t_a > t_d$) after the explosion (t_d), the pressure at a given location jumps to a peak value of overpressure above the local ambient pressure, P_0. The pressure then decays to ambient levels in time t_d, to a partial vacuum of very small amplitude, and eventually returns to P_0. P_s is usually termed as the peak overpressure. The portion of the pressure-time history above initial ambient pressure is called the *positive phase* of the duration . The portion of the overpressure below zero is called the negative or *suction phase*.

In order to study the effects of the blast wave on a structure, it is necessary to know the properties of the blast, such as density, wind velocity, shock front velocity, peak over pressure, and dynamic pressure. The decay of the overpressure most commonly ascribed to the blast wave can be described as quasi-exponential decay as:

$$P_s(t) = P_s(1 - \frac{t - t_a}{t_d})e^{-\alpha \frac{t - t_a}{t_d}} \qquad (1)$$

where α is the dimensionless wave form parameter, t is the time measured from the instant the shock front arrives. It has been suggested [1, 3, 4, 9, 22, 23, 27, 32, 33, 35-37, 38, 44, 52] that the overpressure-time curves can be represented by triangular equivalents. These equivalent triangles have the same initial peak overpressure but have different duration depending on the expected time of maximum structural response. These durations are determined as follows:

(a) if maximum response occurs after the overpressure has decayed to zero a duration t_i is selected so that the total impulse of the equivalent triangular curve is equal to that of the actual curve

$$t_i = 2i_s / P_s \qquad (2)$$

where i_s is the impulse per unit of projected area obtained by integrating $P_s(t)$ from t=0 to t= t_s.

(b) if maximum response occurs early in the pressure-time history the slope of the equivalent triangular pulse is assumed to be tangent to the actual curve, resulting in the duration t_∞.

Equivalence with TNT Explosions

In [8] it is pointed out that most of the data pertaining to explosions deal with the use of TNT explosive, consequently the data for any other explosive needs to be related to that of an equivalent TNT explosion. This is done by relating some measure of the explosive energy produced with that produced by an equivalent amount of TNT. The equivalency of material compared to TNT may be affected by other factors such as the material shape (flat, square), the number of explosive items, explosive confinement, nature of source and the pressure range being considered [3, 24]. The effects of the energy output of explosive material, relative to that of TNT, can be expressed as a function of the heat of detonation as follows:

$$W_{TNT} = \frac{H_{\exp}}{H_{TNT}} w_{\exp}$$

where w_{TNT} is the equivalent TNT charge weight, H_{TNT} is the heat of detonation of TNT, and H_{exp} is the heat of detonation of the explosive. The heat of detonation of common explosives and chemicals can be found in [3, 24, 27].

Blast Scaling Law

Characteristics of the blast wave generated in an explosion depend both on the explosive energy release and on the nature of the medium through which the blast propagates. These properties are measured under controlled conditions in experiments (providing a reference set of explosion data) that can be used to obtain data on other explosions using *scaling laws*. A comprehensive description dealing with the blast scaling methods can be found in [3, 4]. The most common form of blast scaling is the *cube root scaling law*. This law states that *when two charges of the same explosive and geometry, but of different size are detonated in the same atmosphere, the shock waves produced are similar in nature at the same scaled distances.* The scaled distance or the proximity factor Z, is defined as

$$Z = \frac{R}{\sqrt[3]{W}}$$

where R is the distance from the center of the explosion to a given location and W is the weight of the explosive. In addition to this, the explosive yield factor λ., is useful in blast scaling. This is defined as

$$\lambda = \sqrt[3]{\frac{W}{W_r}}$$

where W_r is the weight of the reference explosion. Thus similar shock effects are seen at similar scaled distances

$$Z = \frac{R}{\sqrt[3]{W}} = \frac{R_r}{\sqrt[3]{W_r}}$$

where R_r is the distance of the reference explosion, and is related to R through;

$$R = \lambda R_r$$

Scaling applied to time parameters follows a similar law. The scaled time τ_{sc} for a time t is given by

$$\tau_{sc} = \frac{t}{\sqrt[3]{W}}$$

This implies that the arrival time and duration time (t_a, t_d), can be written as

$$t_a = \lambda t_{ar}$$

$$t_d = \lambda t_{dr}$$

Damage Assessment Methods

The survey of available literature on relevant damage assessment methods as applied to structures subjected to blast loading is somewhat limited. Most of the articles focus on either the potential and observed failure mechanisms or on the use of various constitutive models to characterize the inelastic material behavior. A substantial number of articles address the issue of how finite element analysis can be used to address the behavior of structures subject to blast loading, through the use of refined elements, hybrid material models and use of special elements to allow changes in the integrity of the structural members. An attempt was made to review some of the related articles in the arena of damage models in seismic applications. Unlike the blast loading cases, there are a multitude of articles which address the damage assessment methods, some of these may be useful for the blast loading applications. The results of the literature review are categorized under three topics, (i)constitutive models, (ii)failure models and (iii)damage criteria. While several papers do address some or all three of these areas, the above taxonomy will be used to group based on the primary focus of the articles' content.

Constitutive Models

Material models [10, 25, 50] for civil structures are broadly divided between those for steel and for concrete. Many of these models have been proposed and used for many years. These include both continuum and layered approaches useful in the numerical computation of these models. The models for steel typically range from ideally elastic/plastic, strain hardening, shear stiffness degradation, as well as inelastic models with multiple linear regions (developed for aluminum members). Those for concrete include elasticity, classical plasticity, cap plasticity, bounding surface plasticity,

endochronic theory, fracture mechanics, continuum damage mechanics, and viscoplasticity. Many papers have been presented of late in the latter area [21, 49]. Several hybrid models have been proposed in recent years which have sought to combine two or more of these approaches, in order to predict the behavior in specific load and strain regimes [12, 14].

Failure Models

A majority of articles in this area focus on identifying potential failure mechanisms based on the nature of the loading and the expected structural response of the structure**.** [30, 60, 61] are examples wherein the failure modes for different structures are analyzed based on local material failure as well as fracture, buckling and yield line analyses. These range from failure mechanisms for specific structural configurations (sandwich plates in [60] to general purpose beam analysis). Such analysis [25, 46] has been extended to moderate to deep beams as well as layered Timoshenko beams. Application of such beams within reinforced concrete has been addressed wherein the rebars are analyzed primarily as axial members with some shear stiffness within the concrete continuum. On the dynamic analysis side, the duration of loading combined with the expected natural frequency of the structure determine the validity of assuming the blast loading to be either impulsive or quasi-static. The former case is justified when the natural frequencies of the structure are such that the positive phase duration of the blast is much smaller than that of the structure, thus, ensuring very little response during the loading phase. The latter case corresponds to very long positive phase duration of the blast relative to the structural response times.

Damage Criteria

Almost all of the articles surveyed in this area were applications to seismic loading of structures. However, some of these were general enough to be applicable to other cases. The articles ranged from the use of ductility factor for damage assessment, energy based damage models, as well as combinations of displacement and energy criteria for damage

assessment. The energy based damage models include adaptations of classical low cycle fatigue [26, 29, 51], models based on energy dissipation [16], models based on stiffness degradation under reversed cyclic loading [5, 45], vibrational characteristic based models [18], other hybrid models combining such structural parameters [14], and combinations of excessive deformation and cumulative plastic strain [12, 39, 40]. A different approach described in [47, 56, 62] offers some potential for application in blast loaded structures, especially when used in conjunction with large numerical analyses. In this article the authors describe an approach based on neural networks, which use patterns in response data to provide regression analysis and damage indices useful for damage assessment.

Conclusions

There is no dearth of articles in the area of analysis of blast phenomenon, however, there is broad consensus on the representation of the blast loads on structures. Several methods have been used to actually analyze the blast phenomenon, ranging from the application of simple beam theory, to the use of hydrocodes such as DYNA-3D. In the area of damage assessment models, many material and constitutive models currently exist. More are also being developed each day to overcome specific deficiencies in highly nonlinear material behavior, leading to better understanding the failure under extreme shock or blast loading. However, a much smaller subset of articles address the methods that can be used for damage assessment. The two main approaches here seem to be (i) use of stochastic damage parameters and (ii) use of simplified failure mechanisms in conjunction with either displacement/strain based or energy based criteria. Nevertheless, none of the articles surveyed provides a consistent approach to damage assessment that can be applied using large computational methods based on high performance computing, and visualized in a manner that yields relevant information on the damage phenomena effectively.

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