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Recent observations on design and analysis of protective structures

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ABSTRACT

Recent studies at the Center for Infrastructure Protection and Physical Security (CIPPS) have focused on both active and passive protection, the definition and characterization of combined blast and fragment loads on structural elements, the influence of Ultra High Performance Concrete (UHPC) on the behavior of structural elements, and evaluating analysis approaches for progressive collapse assessment. Those studies have highlighted important issues that have not been sufficiently addressed previously, and this paper is aimed at describing the observations from the CIPPS studies that could be used to treat such difficult issues.

1. Introduction

Protected facilities are expected to perform their function under very severe dynamic loading environments, as extensively described in the literature [1–8]. These loading environments have continuously become more severe, as directly related to the evolution in weapon systems and the escalation in terrorism capabilities. Consequently, one is required to enhance the levels of protection by employing increasingly more sophisticated and more expensive approaches. From a structural engineering standpoint, one needs to satisfy the following underlying equation of equilibrium between the applied loads and a structure's ability to resist them:

$$M\ddot{u} + C\dot{u} + Ku = F \qquad (1)$$

This equation could represent either a single-degree-of-freedom (SDOF) approach or an advanced analysis approach (e.g., finite element or multi-Physics programs). In which, M is the mass (equivalent or mass matrix), C is damping (coefficient or matrix), K is stiffness (coefficient or matrix), and F is the load (single parameter or vector). $\ddot{u}, \dot{u}$ *and*, u are the acceleration, velocity, and displacement (at a point or vectors), respectively. One should note that Eq. (1) needs to be adjusted to accommodate combinations of material and geometric nonlinearities, and represent time-, and/or rate-dependent changes in any of these parameters. In SDOF approaches, the term Ku can be replaced by the nonlinear resistance R that must be derived for the structural system under consideration.

Traditionally, structural/protective engineers have attempted to adopt approaches that could affect both sides of the equilibrium equation by reducing the magnitude of the applied loads, and/or enhancing the structural resistance. Typically, such enhancements were passive; e.g., increase the standoff distance to the explosive device, or shield the structure, to reduce the load magnitude, and/or use stronger structural elements (with combinations of innovative materials, dimensions, and detailing) to enhance the resistance. In recent years, however, also active means have been introduced to further reduce the magnitude of the load (either by intercepting the ordnance, or by suppressing the blast effects).

Several observations from recent studies at CIPPS have been selected for this paper to address the loading and structural resistance issues, and they are presented in separate sections, below. It should be noted that many very important studies on these and related issues have been carried out in recent years by other investigators, and addressing them in a short technical overview would not do them justice. Nevertheless, a few references to other such studies have been included, where appropriate, to provide a technical context to the described findings. Finally, these observations

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are discussed to explore possible implications on the evolution of protecting critical infrastructure systems in the future.

2. Observations related to explosively-induced loads

2.1. Combined blast and fragment effects

Current design manuals and related practical explosive load simulation tools, as mentioned earlier, consider only the blast for loading the structure, while fragments are considered only for penetration. However, observations from the effects of combined blast and fragments on structural targets noted much more severe damage from the combined effects than from blast only. This issue was studied experimentally to understand the synergistic effects of a combined blast and fragment loading [9,10], and the test data showed that cased charges with various case weight combinations with the same amount of explosive material delivered to targets at different standoff distances up to four times the amount of impulse, as compared with the same bare charge at the same standoff distances. Also, it was noted that fragments and blast may arrive at the target at different times, depending on charge weight, case characteristics, and target distance from the charge. For close-in targets, the blast arrived first, followed by fragments. While for far-range targets fragments arrived first, followed by blast. Obviously, there is an intermediate range where both blast and fragments arrived at about the same time. Those findings were later supported by a study [11] that included the development of an innovative sensor capable of measuring pressures induced by blast and fragments. The tests used both bare charges and improvised charges that projected both blast and well characterized fragments onto the target (i.e., roller bearings whose mass was known, and the velocity was measured with flash X-Rays and high seed video). That study highlighted the relative contributions of blast and fragments to the impulse deposition on a target, and provided a direct relationship between those loads and the magnitude of target response. Also other studies attempted to address the combined effects of blast and fragments [12–14], and they showed that combined blast and fragment effects produced enhanced damage to concrete targets. The studies described in [12,13] included explosive devices (cylindrical charges, both bare and with roller bearings) that projected either blast or combined blast and fragments onto concrete targets. The damage to the targets was documented and characterized, and the tests were simulated with hydro code that included advanced material models for comparison with test data. They concluded that the impulses from blast and fragments could be added. The study in [14] had a similar objective to those in [12,13], but it used ConWep [15] to compute the blast and fragments produced by a cased munition, and the penetration depth into a target to extract an approximate force produced during the penetration. Then a single-degree-of-freedom approach was used to find the combination of blast and fragments that produced the maximum target deflection, and a hydrocode was used to validate and calibrate the approach. One should note that the very interesting studies in [12–14] did not address the previous findings in [9,10], they had to rely on hydrocode simulations to assess structural responses, and did not proposed a practical computational approach to predict the load from combined blast and fragment environments.

A more recent study [16] attempted to simulate impulse deposition on the target in [9] by blast and fragments, using the separate procedures for treating blast and fragments provided in [3] and the computer code ConWep [15]. One should note that these approaches enable one to compute the blast time of arrival and its time-history on the target, as well as fragment weight, velocity, and penetration depth, similarly to the procedures used in [14]. The number of fragments to hit the target was computed from the total number of fragments generated from the cylindrical case, and the geometric sector between the charge and target. Then, it was necessary to extract a loading component from the penetrating fragments from the appropriate times of arrival, penetration depths, an approximation of fragment penetration durations, and the total impulse delivered to the target was calculated. It should be noted that the total impulse from the pure blast effect in the proposed procedure was obtained by taking an average of the spherical and hemispherical bursts, as computed with ConWep [15]. This process was repeated for several charges (bare, light case, and heavy case) and standoff combinations, as reported in [9]. An example of results from that study illustrates the combined blast and fragment phenomenon, and the effectiveness of the adopted approach. The impulse due to pure blast from a 0.98 kg CompB charge recorded in the test (MK0) [9], as a function of standoff distance, is shown in Fig. 1 by the Orange[1] solid line. The total impulse due to synergetic effects of both fragmentation and blast recorded in test (MK4) for a 0.98 kg CompB charge and a 4 kg case is shown by the Green solid line. The impulse due to pure blast and the synergetic effects obtained in the proposed procedure are shown by the Blue dash line and Red dash line, respectively. The force delivered by the fragments was derived based on the number of representative fragments that hit the target with their corresponding striking velocity, and transferring their impulse to the target during their penetration time into the target. This example highlights that the combined blast-fragment effects in the range between 2 m and 4 m delivered between 3.4 and 4.7 times total impulse to the target, respectively, as compared with the impulse delivered by the bare charge. Clearly, the combined blast-fragment loading effects are much more severe because they include the pressure on the target from both the blast and fragments. Furthermore, one must address also the added damage, due to fragment penetration, and its effect on the structural resistance of the target, as noted in [12]. Therefore, current design guidelines should be updated to enable analysts and designers to address this much more severe loading combination.

3. Blast load suppression

3.1. Active suppression

Blast suppression by shielding the target with a water mist, or foam suspension mist, were of interest for many years. This concept was studied by several research teams (e.g., [17–25]), and the results showed some promise. The available data indicated that using a water mist barrier between the blast source and the target could reduce the peak pressure by about 30–58%, as shown in Fig. 2. A careful analysis of those studies showed that the main source of pressure reduction was based on momentum transfer between the shock wave and the water droplets, and the mechanical energy used to break up droplets into smaller droplets. Nevertheless, extracting thermal energy from the blast wave also contributed to the pressure reduction, but this phenomenon was more difficult to control. Although very encouraging, the approach needs to be developed further to achieve a more effective blast suppression that might be able to approach an overpressure reduction factor of between 3.5 and 9.8 that was achieved in small scale laboratory tests.

3.2. Passive load transfer limiters

Mechanical load transfer limiters have been used extensively for protecting critical infrastructure facilities against seismically-induced ground motions. Similar approaches were adopted also

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[1] For interpretation of color in 'Fig. 1', the reader is referred to the web version of this article.

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