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Effects of transverse reinforcement spacing on the response of reinforced concrete columns subjected to blast loading

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ABSTRACT

Concerns have risen from building responses and resulting fatalities in some recent infamous terrorist attacks. The collapse of the Alfred P. Murrah Building, for instance, revealed that failure of load-bearing members could lead to extensive building failure. It has become imperative to investigate the blast resistance offered by loading-bearing structural members designed for gravity loads and other load types such as earthquakes.

Reinforced concrete (RC) columns not forming part of the seismic force resisting system were detailed according to CSA A23.3-04 – Design of Concrete Structures. Using a high-fidelity physics-based finite element code, LS-DYNA, a numerical study was undertaken to investigate the effects of transverse reinforcement spacing on the blast resistance of RC columns.

The study shows that the effect of transverse reinforcement spacing and axial loading significantly affects RC column behaviour under blast loading at low scaled distances. At higher scaled distances, however, the effects were insignificant.

1. Introduction

Explosions, whether accidental or planned, can cause significant damage to the built infrastructure and result in fatalities to occupants of buildings in close proximity to the centre of explosion. The increase in the number of terrorist attacks over the past few decades has led to growing concerns about the performance of buildings designed for aesthetics and economy when subjected to blast loading. The United States Federal Emergency Management Agency (FEMA) reports that approximately one in every two terrorist attacks involves the use of explosives [1]. Thus, if a terrorist action is suspected, it is very likely to involve the use of explosives. Furthermore, the terrorists attacks on the Alfred P. Murrah Building in Oklahoma City and the World Trade Centre in New York City and many more around the world have revealed the blast load vulnerability of buildings designed and constructed without due consideration to blast loading. Many researchers are, thus, seeking to understand the behaviour of structural elements under blast loading and to develop mitigation/retrofit measures to protect critical buildings and infrastructure systems against blast loading.

Retrofitting an existing building for improved blast resistance can be expensive. However, as structures designed to resist one load type can often have capacity to resist a different load type, it is important to establish the blast resistance of structural elements designed for other load types; e.g. seismic loads. Buildings designed to meet strength and ductility requirements, depending on the seismicity of a particular region and the importance of the building, could have inherent capacity to resist blast loading. A review of the literature shows limited research work conducted to investigate the performance of seismically designed and detailed structural elements, in accordance with the Design of Concrete Structures [25], under blast loading. More specifically the blast response of elements not forming part of the seismic force resisting system (SFRS) but expected to undergo the same amount of lateral drift have not been extensively studied. Examples of such structural elements are reinforced concrete (RC) columns in buildings with shearwall SFRS.

The lack of experimental research into the blast resistance of building components stems from lack of access to test sites, the high cost of transportation of specimens to the site, rental of heavy equipment to setup experimental tests, and hazards associated with explosion testing. These constraints limit the number of tests that can be performed and the number of parameters that can be investigated in each test program. With recent developments in computer software and hardware technology, numerical modelling

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techniques present a viable and cost effective alternative to explosive field testing. Numerical modelling offers researchers the ability to conduct an extensive investigation of many design parameters at a significantly lower cost.

A general-purpose high-fidelity physics-based finite element package, LS-DYNA, was used to model and investigate the effects of blast loading on RC columns detailed for various levels of seismicity in accordance with the Canadian concrete design code [25].

The RC columns investigated in this paper do not form part of the SFRS but are detailed with sufficient ductility to attain the deformations of the SFRS in the event of an earthquake. The RC columns were modelled with transverse reinforcement detailing representative of columns detailed as conventional and seismic columns at various levels of seismicity. The numerical models were validated with experimental results from live explosion field testing [2].

2. Objectives

The objectives of the research work reported in this paper were, primarily:

- To investigate the effect of seismic detailing (transverse reinforcement spacing) of RC columns, in accordance to CSA A23.3 [25], on their response to blast loading,
- To investigate the effect of axial loading, representative of axial loads on columns of low-rise to mid-rise building, on their response to blast loading.

3. Literature review

The study of the blast resistance of conventionally designed structures has become significantly important in recent years in light of the increase in global terrorism. Conventional structural design principles require loads to be transferred safely to the foundations through defined load paths and in such a way that failure of one component does not lead to failure of a disproportionate part or of the entire structure. Thus structural components such as columns are detailed with stringent performance requirements. RC columns on the periphery of a building could be exposed to high blast loads from proximate explosions and their failure can lead to progressive or disproportionate collapse. Many researchers [3–5] have identified failure of RC columns under blast loading as a potential precursor to progressive collapse. Failure of a load bearing precast wall due to internal gas explosion caused the partial collapse of Ronan Point Towers in East London [3] while the collapse of a peripheral column supporting a transfer girder is reported to have caused the progressive collapse of the Alfred P. Murrah Building in Oklahoma City [6].

3.1. Explosions and mechanism of blast loading

Conventional structural design does not include loading from explosion events. Thus few buildings are designed with the requisite resistance against blast loading. Exceptions to this are buildings in petrochemical facilities where explosion hazards exist and high profile buildings such as embassies. The explosion process, blast wave evolution and interaction with structures is, thus, not widely understood by the structural engineering community.

A chemical explosion is described as the rapid oxidation of explosive material and the release of high amounts of energy in the form of heat and light [1] within a very short period of time. The chemical reaction results in increase in atmospheric pressure and temperature and expansion of the surrounding air. The high speed expanding air compresses the leading air into a thin shock front. When the shock front reaches a point in space, remote from the centre of explosion, the atmospheric pressure instantaneously increases to the incident pressure value followed by an exponential decay back to atmospheric conditions. The time within which the pressure is above atmospheric characterises the positive phase and duration of the blast [7,8]. When the shock front impinges on a medium denser than the medium it is propagating in, it is reflected. The peak reflected pressure is higher than the peak incident pressure and depends on the angle of incidence and the magnitude of the incident pressure. The peak reflected pressure can be as high as 8 times the peak incident pressure [9].

Fig. 1 shows a typical blast pressure profile at a point remote from the centre of explosion. The time of arrival (t_a) is the time it takes the blast wave to reach the point of interest. The atmospheric pressure rises instantaneously to the peak incident pressure (P_{so}) or peak reflected pressure (P_r) if it impinges on a reflecting surface. The time during which the pressure is greater than atmospheric is the positive phase of the blast pressure profile with a duration t_d^+ while the time during which the overpressure is below atmospheric is the negative phase of the blast pressure profile with a corresponding duration t_d^-. The impulse of the blast is the area under the blast pressure profile.

The peak value of the blast pressure (incident and reflected) is a function of the charge mass, standoff distance of the structure from centre of explosion, and the angle of incidence to the reflecting surface to the blast wave [8].

3.2. Structural response to blast loading

The blast waves generated from an explosion exert a transient dynamic load on structures. The short duration impulsive load and resulting inertial forces generated due to the acceleration of the structure are resisted by internally generated strain energy [10]. The response of structural elements subjected to blast loading can be investigated through field testing or numerical modelling. The numerical modelling techniques often employed consist of non-linear dynamic finite element analysis or the simpler single-degree-of-freedom (SDOF) analysis. Non-linear finite element numerical modelling techniques provide a less expensive method for investigating the response of structural elements under blast loading in comparison with experimental field testing. The numerical modelling also offers opportunity to investigate an extensive number of design parameters pertinent to blast resistance of structures. Non-linear finite element analysis, however, presents a different set of challenges including: selection of a suitable problem-specific mesh, ability to examine stability of the solution procedure, and assessing all sources of errors based on modelling assumptions [11].

3.3. Column response to seismic loading

Maximum moments in columns with fixed ends occur at the ends when subjected to ground excitation. The columns usually deform in double curvature due to lateral drift from seismic loading. When the end moment resistance of the column is exceeded, plastic hinges are formed and causes further lateral deformations. The column, as a result, could lose its axial load capacity and lead to progressive collapse of other structural elements if the column is a critical load carrying element [12,13].

Thus RC columns are designed and detailed with closely spaced transverse reinforcement in the plastic hinge regions; top and bottom of columns. The mid-height region of RC columns do not require as much transverse reinforcement under seismic loading. However in blast loading where columns deform in single curvature with maximum moment occurring at mid-height, this could be a potential vulnerability.