Engineering Structures 61 (2014) 31–43

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Blast response and safety evaluation of a composite column for use as key element in structural systems

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A R T I C L E I N F O

Article history:
Received 29 May 2012
Revised 6 January 2014
Accepted 6 January 2014
Available online 6 February 2014

Keywords:
Blast analysis
Composite column
Steel core
Residual capacity
Structural collapse
Computer simulations
Key element

A B S T R A C T

This paper presents the blast response, damage mechanism and evaluation of residual load capacity of a concrete–steel composite (CSC) column using dynamic computer simulation techniques. This study is an integral part of a comprehensive research program which investigated the vulnerability of structural framing systems to catastrophic and progressive collapse under blast loading and is intended to provide design information on blast mitigation and safety evaluation of load bearing vulnerable columns that are key elements in a building. The performance of the CSC column is compared with that of a reinforced concrete (RC) column with the same dimensions and steel ratio. Results demonstrate the superior performance of the CSC column, compared to the RC column in terms of residual load carrying capacity, and its potential for use as a key element in structural systems. The procedure and results presented herein can be used in the design and safety evaluation of key elements of multi-storey buildings for mitigating the impact of blast loads.

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1. Introduction

1.1. Motivation for the present work

With an increase in terrorist activity it is necessary to provide adequate capacity to vulnerable columns in buildings to mitigate the consequences of the adverse effects of blast loads. As seen in the past, a bomb explosion in a public building with a high occupancy results in a large number of casualties and property damage. Blast resistant design of structures has therefore attracted significant attention under the present environment of global terrorism [1–5]. Motivated by this interest, a comprehensive research program on the vulnerability of reinforced concrete structural framing systems to blast loading was undertaken. The research presented in this paper is an integral part of that research program to provide design information that can be useful in blast mitigation and safety evaluation of load bearing vulnerable columns that are key elements in a building. Key elements are defined as structural components that cause the collapse of more than a limited portion of a structure within close proximity [6]. Composite columns have been found to have the potential to mitigate the adverse effect of random and unpredictable loads [7]. This paper investigates the blast response and post blast performance of a concrete–steel composite (CSC) column under different blast load scenarios and compares the performance with that of a reinforced concrete (RC) column having the same dimensions and steel ratio, but without the steel core (hereafter referred to as the RC column).

1.2. Background and scope of the present work

Blast resisting capacity with mitigation strategies are important for key structural elements located in critical zones where high intensity blast pressure is directly applied. Different retrofit measures and design strategies have been proposed in recent investigations for safety [8–12]. However, comprehensive and economical design strategies are needed for future construction of buildings to perform effectively at their post blast serviceability state, in order to protect lives and property. The blast and post blast performance of key structural elements are therefore necessary to avoid disproportionate collapse of a building. Post blast evaluation of a structure is vital for post disaster evacuation.

An explosion detonated at ground level will have a critical impact on the lower storeys of the building structure [13]. Catastrophic failure of the structure will initiate at the critically damaged zone due to reduction of the load carrying capacity of the load bearing key structural components such as columns [14] and the structure may yield to progressive collapse. The well-known example is the Alfred P. Murrah Federal Building bombing incident where progressive collapse extended beyond the immediately damaged zones [15]. Progressive collapse of framed structures in general [16] and under column loss in particular [17,18]

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0141-0296/$ - see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.engstruct.2014.01.007

has been treated in the literature. The load bearing structural elements must be capable of carrying the residual gravity loads to prevent their catastrophic collapse that initiates progressive collapse of the entire structure. Columns with adequate residual load bearing capacity in their damaged state are therefore required to carry post blast gravity loads.

This paper is extracted from a three year programme of research that was carried out at the Queensland University of Technology (QUT) to comprehensively investigate the vulnerability and failure of reinforced concrete structural framing systems to near field blast effects. The programme investigated both global and local effects on building structures for preventing catastrophic and progressive failure using established principles and validated computer simulation techniques. Due to associated risks and costs, experimental forms of investigation are prohibitive for research that involve parametric variations such as charge weights, standoff distances, proximity to key elements and dynamic and material response of structural components. Computer simulation has therefore been adopted as an effective and viable method. However, computer simulation of structural framing systems comprising several thousand component elements can become a massive numerical problem when rigorous analysis techniques are used. The QUT research programme therefore used linear simulation techniques to analyse the total and progressive failure of the structural framing system (global analysis) and non-linear computer simulation techniques to treat the key component elements respectively. This effectively reduces the size of the massive computational effort to one that allows iterative simulation and refinement of accuracy and reliability within a reasonable time frame.

Computer modelling for blast analysis identifies coupled or uncoupled analysis systems. In a coupled analysis, both blast load prediction and structural modelling are achieved together in one computer model. An uncoupled analysis treats the modelling and analysis of structures by applying pre-determined loads separately. The uncoupled method was used in the QUT research program due to the complexity of modelling and uncertainties associated with coupled analysis. Furthermore, the focus of this study was the structural and material response of the framing system and components that can culminate in catastrophic collapse. The techniques used in the QUT research program have been compared with the research carried out by others for validation and the details are presented in [19,20].

The first phase of the QUT research program used linear time history analysis for the complete building frame in order to investigate the ability of the structural framing system to regain its elastic strength and restore stability and equilibrium after the event. SAP 2000 code was used for this part of the analysis with multiple evaluations of demand to capacity ratios using dynamic increase factors (due to high strain rates) to identify the vulnerable part of the structural frame together with the component elements [20]. Non-linear rigorous analysis using the LSDYNA code was then used to carry out in depth studies on damage propagation and failure of sub-frame containing the vulnerable key elements, which if damaged can result in catastrophic or progressive collapse of the entire structural frame. The work in the present paper covers the last phase of the QUT research project and was motivated by the need to provide blast mitigation to vulnerable frontal columns (key elements) in a building.

Accordingly, the blast response of a concrete–steel composite (CSC) column, which can be used as a key element in blast mitigation, is treated in this paper using rigorous computer simulation techniques. The composite column is a typical reinforced concrete column, enhanced with an additional structural steel core at the centre. The type of concrete–steel composite (CSC) column investigated is suitable for use at vulnerable locations in a building of 10–15 storeys, for specific column spacing and floor loads. This particular column is suitable for a 10 storey office building and it has a longitudinal steel ratio of 1.8% of the gross cross-sectional area. The performance of a frontal CSC column, symmetrically placed in the ground floor of the building, is evaluated and compared with that of the RC column designed according to Australian Standards [21].

A numerical investigation was conducted by computer simulations using the nonlinear explicit finite element code LS DYNA for the potential threat of a near field blast event. The explosion load cases were derived for different charge weights for a standoff distance of 5 m. The blast loads were different along the height of the column, as the explosion occurred close to the structure. Non-linear time history analysis was conducted for the combined blast and gravity loads. The displacement time histories at the column's mid span and effective plastic strain diagrams and stress plots were selected as response parameters to evaluate the performance of the columns under a range of blast and axial loads.

The results of the analysis showed the disintegration of the concrete encasement away from the steel core and transfer of loads to the residual concrete and core steel section. The post blast performance of the CSC column was evaluated based on the damage to the composite section, and the load carrying capacity of the remaining partially damaged or yielded components of the composite section. The overall results indicate that the CSC column can withstand the lateral blast pressure better than the RC column. The superior performance of the CSC column is due to the presence of the structural steel core which enables its post blast gravity load carrying capacity. This information can be used in the design of vulnerable columns in multi-storey buildings to avoid catastrophic or progressive collapse.

2. Procedure

2.1. Blast response of concrete columns – global and local effects

Structural components subjected to high intensity blast loads may experience local and global effects comprising flexure, direct shear and punching shear failures in relation to loading rate, direction of the blast wave and boundary conditions [22]. Local effects in concrete encased sections are bleaching and spalling [3]. RC columns are vulnerable to flexural failure due to transverse blast load effects. Global failure modes applicable to the concrete column are diagonal tension, diagonal compression and direct shear [4]. Direct shear failure results from transient short duration dynamic loads created by the pressure wave intensity of blast effects. The associated shear force can be higher than that associated with flexural failure modes. High shear stresses may therefore lead to direct shear failure which occurs within a few milliseconds after the arrival of the shock wave at the structure and before significant bending deformations. A near field explosion may cause localised shear or flexural failure of the column. The punching effect is frequently referred to as bleaching, which is well known in high velocity impact applications and near field explosions. Bleaching failures due to the punching effect are accompanied by spalling and scabbing of concrete covers. Cracking, spalling and bleaching of concrete will tend to reduce stiffness and increase damping of the column. These factors are usually evaluated when adopting a solution based on an un-damped single degree of freedom system. However, there is insufficient time for stiffness degradation and damping to have any effect on the structural response due to the high strain rate associated with blast loading. Strength degradation due to cracking, spalling and bleaching of concrete needs to be evaluated when calculating residual load carrying capacity of key elements in the post blast serviceability state.

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