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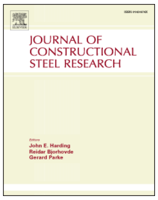

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Behaviour and analysis of concrete-filled rectangular hollow sections subject to blast loading

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ABSTRACT

Concrete-filled Rectangular Hollow Sections have been tested under large-scale, far-field, air-blast loading for the first time. The concrete-filled, cold-formed steel tubes performed well under the blast loads, with a significant reduction in the global and local displacements compared to unfilled RHS members. The heavily instrumented tests provided a large quantity of response data that was used for the validation of numerical models. Numerical models of the concrete-filled steel tubes were first developed using explicit finite element methodologies. A parametric study was conducted with the validated finite element model to further characterize the response of the concrete-filled steel tubes under air-blast loading. The influence of several key variables on the response of the tubular members was determined and preliminary design guidance is provided. Finally, the test and finite element results were used to develop an idealized single-degree-of-freedom numerical model that is well-suited to future use in design problems.

1. Introduction

Increasingly, protective design measures, with respect to accidental or malicious blast loading, are being incorporated into civilian infrastructure. Protective design requires an integrated approach that involves engineers, architects, security consultants, and risk analysts, amongst others. Firstly, a risk analysis is completed that determines the threat to a building and potential scenarios. Various architectural defensive strategies are then reviewed. This ultimately results in a loading case for blast design, with an assumed charge-weight and standoff distance for critical locations within and around a structure. Finally, load transfer mechanisms from non-structural components such as cladding are assessed to determine the blast load felt by structural members.

The desire to strike a balance between the architectural and protective design requirements necessitates an understanding of typical structural elements subject to blast loading. Steel structural systems, due to the steel's energy dissipating characteristics, have been cited as an ideal choice for protective design [1,2]. Another critical characteristic of blast response is mass. Composite steel elements, particularly concrete-filled steel tubes (CFST), combine the benefits of the steel ductility and the concrete mass with a minimal restriction on the architectural design. Concrete-filled Rectangular Hollow Sections (RHS) are a practical choice because they also have strong torsional characteristics and square RHS have no weak axis in flexure. This is ideal for protective design since the exact source of an explosion is often unknown.

Current protective design procedures rely heavily on empirical solutions and research that is not publicly available, hence, research is necessary to improve on these design practices. While there has been research on the impact response of small concrete-filled RHS [3–6] and larger concrete-filled RHS under near-field blast loading [7–9], there is little work on the far-field air-blast response of concrete-filled RHS. Research has also been conducted on the impact [10–12] and near-field blast [13] response of concrete-filled Circular Hollow Sections (CHS). Table 1 highlights the important details of this existing research on concrete-filled Square Hollow Sections (SHS) and CHS, including material grades and strengths. Full-scale composite elements subject to far-field air-blast loading will have a different response than these tests under impact or near-field blast loading. Thus, new research was initiated to investigate concrete-filled RHS subject to air-blast loading.

The high cost of testing under blast conditions necessitates the use of numerical modelling to expand on experimental results. The most common numerical method for detailed analysis is explicit finite element

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Table 1
Previous experimental research on concrete-filled SHS and CHS subject to blast and impact.

Loading type	Cross-section shape	Tube material	Steel yield strength, f_y (MPa)	Concrete compressive strength, f'_c (MPa)	Reference
Lateral impact	SHS	Cold-formed C350	473	88	[3]
	SHS	Mild steel	440	41	[4]
	CHS	Steel	340	58	[10]
	CHS	Cold-formed steel	232–298	38	[11]
	SHS	Grade 304 stainless steel	610	41	[5]
	SHS	Cold-formed steel	349	16	[6]
	CHS	Cold-formed steel	247	55	[12]
Near-field	CHS	ASTM A500	254–419	42	[13]
	SHS	Cold-formed, C350	424	46	[7]
	CHS/SHS	Steel	312–485	36	[8,9]

(FE) modelling. Several commercial FE programs are available and commonly used in protective design including ABAQUS [14] and LS-DYNA [15]. The studies outlined in Table 1 all include numerical studies or have separate numerical studies based on their experimental work [16–18].

The research on the far-field air-blast response of concrete-filled RHS elements presented herein contains four components: field testing, a finite element (FE) test analysis, an FE numerical parametric study, and the presentation of a single-degree-of freedom (SDOF) design procedure. Field testing was completed using a blast arena test setup. Explicit FE analysis numerical models, were then developed and compared against the test results. Once validated, the FE models then served as the basis for a parametric analysis. Conclusions on the behaviour of composite RHS subject to far-field air-blast loading are drawn from these parametric studies. Finally, SDOF numerical models were compared against both the test and FE results, and a design procedure is presented.

2. Field blast testing

A series of field blast tests were conducted on concrete-filled RHS elements in flexure, at a test range in the Negev Desert, Israel.

2.1. Test specimens

Two RHS sizes, RHS120 × 120 × 5 and RHS120 × 120 × 8, manufactured to EN10219 [19] Grade 355J2H, were used to construct the concrete-filled RHS members. Laboratory tests were performed on segments of un-blasted cold-formed steel material to determine the mechanical and geometric properties of the RHS elements. Five quasi-static tensile coupons tests, three taken from the RHS flats and two from the corners, were conducted to ASTM A370 [20] for both RHS sizes. Corner coupons were tested while maintaining their curved shape in the testing machine grips. The resulting stress-strain curves are shown in Fig. 1. The 0.2% offset method was used to determine the yield strength. These values, along with the modulus of elasticity, ultimate strength, and elongation at failure are summarized in Table 2. The geometric properties of the RHS elements were also carefully measured for use in numerical modelling.

The compressive strength of the concrete filling of the RHS elements was tested to EN12390-3:2009 [21], giving a 28-day cube compressive strength of 36.1 MPa. The relationships outlined in EN 1992-1-1: 2004 [22] were used to determine the equivalent, weighted compressive cylinder strength (f'_c) of 29.4 MPa. The composite RHS flexural test specimens, which were ultimately field-tested in the vertical position, had a length of 2800 mm between supports, with a pinned connection on the bottom and a slotted connection on the top, as illustrated in Fig. 2. Including the pinned and slotted connections the total span of the RHS members was 3260 mm.

An investigation into the composite interaction between the RHS element and the concrete filling was also performed on one of RHS120 × 120 × 5 members. A small section of a tested member which had experienced just elastic loading was sawn from a tested element. A quasi-static push-out test was then conducted in the laboratory and the results are illustrated in Fig. 3. The average tangential bond stress, as illustrated by the linear best fit line was 0.41 MPa. This value exceeds

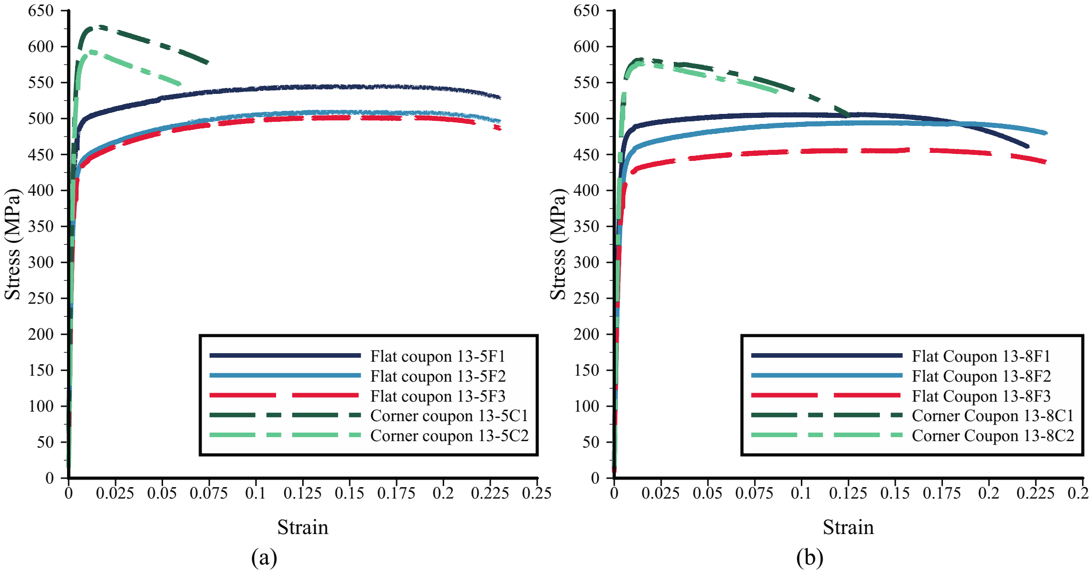

Fig. 1. Cold-formed RHS steel stress-strain curves: (a) RHS120 × 120 × 5; (b) RHS120 × 120 × 8.