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Performance assessment of steel plate shear walls under accidental blast loads

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ABSTRACT

Previous research on properly-designed steel plate shear wall systems has proven that it has a high level of lateral shear strength and stiffness and large ductility. These properties, along with ample redundancy, robustness, and superior energy dissipation capacity under severe cyclic loading, have made the system a viable lateral force resisting system for seismically-active regions. Although similar properties are desirable for protective structures, their application in this regard has been largely neglected. The potential application of some form of the steel plate shear wall as a protective system in industrial plants possibly subjected to accidental explosions is studied by means of iso-response curves. To capture all important aspects in blast response, a comprehensive numerical model is developed. The constitutive model for the steel material includes mixed-hardening, strain-rate effects, and damage initiation and evolution. The pressure–impulse diagrams for both in-plane and out-of-plane blast orientations, along with the corresponding weight–standoff distance diagrams, are produced with the aid of the numerical model. Different response criteria and wall sizes are considered. A method is proposed to produce dimensionless iso-response curves to broaden their applicability. The results show that despite the inherent slenderness of the steel members, the wall system has the potential to be an effective system for use in a protective structure for industrial plants, especially for the in-plane blast load condition.

1. Introduction

Steel plate shear walls (SPSW) have been advanced through the last two decades primarily based on research that focuses on improving their performance under severe earthquake loading. Previous research has shown that the system possesses exceptional ductility and lateral force resistance, with a high level of energy dissipation capacity without degrading under cyclic loading. As such, the system has reached a stage where design standards, such as Canadian Standard S16 [1], have assigned it the highest ductility-related and overstrength-related force modification factors of any seismic system. Although it is undeniably well-suited for high seismic regions, and similar properties are advantageous for resisting other types of dynamic loading such as blast, their potential applications as protective structures have received little attention.

Most of the structures in industrial plants are made up of steel systems, which normally have rapid erection times and tend to be more flexible than concrete construction in terms of future expansion and site rearrangement. Therefore, having a reliable protective structural steel option available would be advantageous economically. Through the process of site planning, protective structures in industrial plants are sited at a suitable distance from process equipment and any source of release of flammable or explosive material. As such, the blast loads that need to be considered in the design of industrial structures tend to be "accidental" far-range (low pressure) detonations and are less detrimental for slender steel members than near-range (high pressure) explosions. Protective structures are prone to localized damage and failures under blast loading, but their overall integrity must not be compromised if they are to fulfill their intended function. To limit the damage and improve the reliability of the system, a high level of redundancy is beneficial for blast-resistant systems to ensure the availability of alternative load paths. As such, the SPSW, which is a continuous system with a high level of ductility capacity, is potentially a good candidate as a primary component of protective structures in industrial plants.

This research is an exploration of the inherent qualities of conventional SPSWs for use as protective structures, with the additional goal of identifying where modifications are required for optimal performance in this new application. This is achieved through the development of pressure–impulse (*P–I*) diagrams. First, the *P–I* curve is described in detail and is generalized (normalized) by transforming a wall system into a single-degree-of-freedom (SDOF) system. A comprehensive numerical model that is able to capture all critical aspects of the blast response is developed. The in-plane and out-of-plane responses are investigated separately. *P–I* diagrams for two different-size walls have been developed and normalized. They are then converted to charge weight–standoff distance curves. The results show that a

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properly-designed and detailed SPSW may indeed be a viable protective system for accidental blast in industrial plants such as petrochemical facilities.

2. Literature review

2.1. Performance criteria

The maximum dynamic responses of structural components intended to resist the blast loading need to be limited against the desired blast levels of protection or blast design objectives. These response limits are typically called "performance criteria," and are defined in blast design guidelines. Generally, when components are under large shear or compressive forces, the response limits are small and barely reach the yield point, while large deformation limit values are permitted for components loaded mainly in flexure. Additionally, other factors, such as the siting distance from the blast source, occupancy of the building, and importance of the equipment protected by the building, affect the blast design requirements.

The American Society of Civil Engineers' (ASCE) document for blast design of petrochemical facilities [2] defines the allowable deformation of individual components based on the desired level of protection and type of component for different construction material types. Three performance levels, or damage levels—namely, low, moderate, and high response ranges—have been considered. The performance levels are conceptually similar to the immediate occupancy, life safety, and collapse prevention performance levels, respectively, used in performance-based seismic design [3]. The low response range corresponds to a high degree of blast protection with only localized damage. The medium and high response ranges represent widespread damage and loss of structural integrity, respectively. Two dimensionless response parameters—namely, the ductility ratio, μ, and support (chord) rotation in degrees, θ—have been defined at each performance level. The ductility ratio is the ratio of the maximum component deformation to its yield deformation, which is a measure of the capability of the component to experience inelastic deformation and absorb energy with no significant capacity loss. The tangent support rotation is a measure of both rotational ductility at the support and the degree of potential instability in the member. Building performance criteria are also defined in the ASCE document according to the inter-story drift ratio. For example, the lateral drift ratios of moment-resisting structural steel frames are limited to 2.0%, 2.85%, and 4.0% for the low, medium, and high response ranges, respectively. The response limits have been elaborated from the first edition of the document published in 1997, and the changes have been described in detail by Oswald [4].

The response limit for an individual structural steel component based on various design guidelines are shown in Table 1. The column "LP" shows the component Level of Protection, where "H", "M", "L", and "VL" represent High, Medium, Low, and Very Low levels of protection, respectively. The column "Resp. Param." shows the different response parameters at each level of protection, which are the ductility ratio, μ, and support chord rotation, θ (°). Because of different definitions of damage or performance level in the various design guides, direct comparisons of the response limits shown may not be absolutely consistent; the table is intended for general comparisons only.

For the response limits proposed by the ASCE blast design manual [2], the performance levels are identified in table column "Perf. Level", as "Low Resp.", "Med. Resp.", and "High Resp.", which correspond with the high, medium, and low levels of protection, respectively. The manual provides defined response limits for different hot-rolled steel components, including compact secondary flexural members such as beams, girts, and purlins (column "BM Sec."), primary frame members with and without significant compression (column "Prim. Mem."), and plates (column "PL"). Significant compression is defined as a force larger than 20% of the dynamic axial compressive capacity of the member, where the axial force is evaluated from a capacity method based on the ultimate resistance of the supported members exposed to the blast loads.

The UFC 3-340-02 document [5] presents methods of design for protective construction against accidental explosion of high-explosive (mainly military) materials. Two levels of protection have been considered for blast design. Structures designed to protect personnel against accidental blast are classified as Category 1, while structures provided to protect equipment are designated Category 2. The response criteria proposed by this document are shown in Table 1, where the column "Prot. Cat." shows the protection categories, and columns "BM" and "PL" show the response limits for beams and plates, respectively. Categories 1 and 2 ("Cat. 1" and "Cat. 2", respectively, in the table) correspond to medium and low levels of protection, respectively.

The PDC TR-06-08 document [6] defines response criteria against explosive terrorist threats in terms of ductility ratio and support rotation for four different component damage levels, including Superficial, Moderate, Heavy, and Hazardous, as shown in Table 1. Different structural component types and characteristics have been considered for both primary and secondary elements. Table column "Comp. Dam." shows the component damage levels, where columns "BM", "CPR", and "PL" show response limits for primary compact beam elements, compression members, and plates, respectively. (The document also suggests response limits for non-compact, secondary, and non-structural components, not shown in the table.) The moderate and heavy component damage levels correspond roughly to the medium and high response performance levels, respectively, in the ASCE petrochemical design guidelines [2]. However, the superficial damage level represents more conservative design limits (i.e., lighter damage levels) than the low response performance level in the ASCE manual [2], but both can be classified as high levels of protection. Since the response

Table 1
Response limits for hot-rolled structural steel members in various blast design guides.

LP	Resp. param.		ASCE (2011) [2]				UFC (2008) [5]			PDC (2008) [6], ASCE/SEI (2011) [7]				ASCE (1999) [8]				NYC (2008) [9]	
			Perf. level	BM sec.	Prim. mem.[a]	PL	Prot. cat.	BM	PL	Comp. dam.	BM[b]	CPR	PL	Dam. level	BM flex.	BM shr.	CPR	BM sec.	CPR
H	μ	–	–	–	–	–	–	–	–	Superficial	1 (1)	0.9	4	–	–	–	–	–	–
	θ	°		–	–	–		–	–		– (–)	–	1		–	–	–	–	–
	μ	–	Low Resp.	3	1.5 (1.5)	5	–	–	–	–	–	–	–	Light dam.	–	–	10	–	–
	θ	°		2	1 (1)	3		–	–		–	–	–		5.7	2.3	–	–	–
M	μ	–	Med. Resp.	10	3 (2)	10	Cat. 1	10	10	Moderate	3 (3)	1.3	8	Mod. dam.	–	–	20	–	–
	θ	°		6	2 (1.5)	6		2	2		3 (3)	–	2		13.5	4.6	–	–	–
L	μ	–	High Resp.	20	6 (3)	20	Cat. 2	20	20	Heavy	12 (3)	2	20	Severe dam.	–	–	40	20	5
	θ	°		12	4 (2)	12		12	12		10 (3)	–	6		26.6	9.1	–	10	6
VL	μ	–	–	–	–	–	–	–	–	Hazardous	25 (3)	3	40	–	–	–	–	–	–
	θ	°		–	–	–		–	–		20 (3)	–	12		–	–	–	–	–

[a] For member with significant compression, the values in parentheses should be used
[b] For combined flexure and compression, the values in parentheses should be used