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Seismic performance of steel moment frame office buildings with square concrete-filled steel tube gravity columns

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ABSTRACT

A dual lateral-force resisting system consisting of a primary lateral-force resisting system and secondary concrete-filled steel tube (CFT) columns placed in the gravity framing is presented in this paper. The dual CFT system concept relies on the primary lateral-force resisting system to supply the main lateral strength, while additional lateral strength and robustness is provided by the CFT columns. To explore the viability of the concept, the predicted seismic performance of 1-story, 2-story, and 4-story office conventional buildings, with perimeter steel moment frames and wide-flange gravity columns, was compared to the performance of the same buildings but employing square HSS columns filled with unreinforced concrete. The analyses predicted that, compared to conventional buildings, buildings with the dual CFT system were 20–83% less susceptible to seismic collapse, depending on the strength and ductility of the primary moment frame, the orientation of the wide-flange columns in the conventional building, and the number of stories. Using high-strength, thick, or slightly larger CFT columns did not significantly improve collapse safety. Buildings with the dual CFT system generally had improved seismic performance, depending on the moment frame design, the number of stories, and the intensity of the ground shaking. Buildings with the dual CFT system had up 45% lower repair costs, up to 64% shorter repair time, and a lower probability that the building would be deemed unsafe.

1. Introduction

1.1. Background

Dual lateral-force resisting systems consisting of moment frames acting with a secondary system, e.g. ASCE 7-16 Table 12.2-1 [1], have two key characteristics that may enhance seismic performance compared to single systems. First, dual systems explicitly can provide increased redundancy [2], allowing load to be transferred through alternate paths that are intended to be part of the lateral-force resisting system. By contrast, a single system may lead to unintentional redistribution of load. In fact, the potential for beams and columns designed to support gravity loads ("the gravity framing system") to act as dual or "reserve" lateral-force resisting system, intended or unintended, has been recognized for several years [3–7]. Second, dual systems may provide added safety against collapse and added resistance to structural and non-structural damage compared to a single system [2]. The latter characteristic is the motivation for the dual system explored in this study.

The effectiveness of a dual lateral-force resisting system that utilizes the gravity framing as the secondary element in the system depends on several factors, including building height, structural configuration, location of column splices, beam-to-column connection details, and the seismic zone [3,4]. Depending on these factors, gravity framing may help reduce residual story drift [5], improve collapse safety [3,6] and improve serviceability [7]. For a dual system that involves a steel moment frame (MF), a previous study [4] showed that the gravity system needs to be capable of resisting at least 10% of the prescribed seismic forces in order to be effective. Dual systems designed according to ASCE 7-16 provisions are required to resist 25% of the prescribed seismic forces. In many cases, however, the lateral capacity contribution of a conventional gravity framing system is modest (on the order of 10–30% percent of the lateral-force resisting system). Furthermore, in many cases soft-story mechanisms limit the ability of the gravity framing to improve global collapse resistance of the building. Thus, previous work indicated that a gravity framing dual system concept may be most advantageous in moderate-seismic zones, as opposed to high seismic zones.

Concrete-filled steel tube (CFT) columns integrated with the gravity framing system may provide a pragmatic approach to both increase the lateral strength of the gravity framing system and improve the global collapse mechanism. Prior research of moment frames with CFT

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columns and wide-flange beams and CFT columns acting alone [8,9] has demonstrated that CFT columns have significant flexural strength, axial compressive strength, and significant strength when subjected to combined axial and flexure loads, while at the same time contributing toward a cost-effective construction method. Perhaps more important in the context of a dual system that utilizes the gravity framing system to deliver additional lateral strength, CFT columns have excellent flexural strength in two orthogonal directions, whereas wide-flange (W-shape) sections have poor flexural strength in the weak direction (minor-axis bending).

1.2. Objectives

The objective of this analytical study was to explore the potential of a dual CFT system, consisting of a primary steel MF and a secondary system utilizing CFT columns in the gravity framing system, for low-rise (1-story and 2-story) and mid-rise (4-story) office buildings located in low and moderate seismic zones. Three types of MFs were considered: (1) a non-ductile steel MF, (2) a ductile steel MF designed for the lowest spectral acceleration in ASCE 7-16 [1] Seismic Design Category (SDC) D, and (3) a ductile steel MF designed for the highest spectral acceleration in SDC D. The focus of the study was on square CFT columns using HSS 14 × 14 × 5/16 with a steel minimum yield stress, F_y equal to 317 MPa (46 ksi) and a concrete compressive strength, f_c' equal to 34.5 MPa (5 ksi). The CFT section was selected based on providing a flexural strength that is comparable to the flexural strength of typical wide-flange columns used in the gravity framing system. The effect of high-strength CFT columns, thick CFT, and slightly larger CFT columns was also evaluated for 4-story buildings. Rectangular and circular HSS were not considered in this study. The seismic collapse safety and seismic performance of the buildings with CFT columns in the gravity framing system was predicted and compared to the performance of "conventional" buildings (with wide-flange gravity columns) using adaptations of the FEMA P-695 methodology [10] to evaluate collapse safety, and the FEMA-P58 methodology [11–13] and companion software, *PACT (Performance Assessment Calculation Tool)* [14] to evaluate repair cost, repair time and the probability of unsafe placarding after an earthquake.

2. Methodology

2.1. Building configuration

The building configuration, shown in Fig. 1, was a rectangular plan with steel moment frames along the perimeter of the building. The structural framing was based on a 6.10-m (20-feet) bay length, a 4.57-m (15-feet) first story height, measured to the top of beam, and a 3.96-m (13-feet) upper story height (Fig. 1a). The building configuration was based on steel MF archetype buildings that were originally designed for a study, commonly known as the "ATC-76 project" [15], that evaluated the FEMA P-695 methodology for conventional lateral-force resisting systems, including moment frames. Three types of moment frames were evaluated in this study:

- Non-ductile moment frame, with fully-restrained directly-welded flange connections, designed for the lowest spectral accelerations corresponding to SDC B (referred to as "SDC B_{min}"),
- Ductile "Special" Moment Frame (SMF), with reduced beam sections, designed for the lowest spectral accelerations corresponding to SDC D (referred to as "SDC D_{min}"), and
- Ductile "Special" Moment Frame (SMF), with reduced beam sections, designed for the highest spectral accelerations corresponding to SDC D, (referred to as "SDC D_{max}").

The sizes of the beam and column members in the moment frame are provided in a prior study [16] and in Appendix D of the ATC project report [15]. The gravity framing system was designed for a 4.31 kN/m^2 (90 psf) dead load and a 2.39 kN/m^2 (50 psf) live load. The roof and floor of the buildings used a 140-mm (5.5-in.) composite slab and gravity framing beams spaced at 3.05 m (10 feet) on center connected to girders with shear tab connections. The gravity framing wide-flange columns were pinned at the base and spliced 1.22 m (4 feet) above the third floor. (In the ATC-76 project, the gravity framing system was not explicitly considered or designed.) The design of the gravity framing system and the sizes of gravity framing beams is provided in a prior study [16]. The sizes of gravity columns ranged from a W14 × 30 to a W14 × 90. Three types of columns in the gravity framing system were considered in this study:

- Wide-flange columns oriented with the weak axis in the same direction as the moment frames (Fig. 1b),
- Wide-flange columns oriented with the strong axis in the same direction as the moment frames (Fig. 1c), and
- CFT columns.

The two orientations (strong and weak) of the wide-flange columns were selected in order to provide an upper and a lower bound on the contribution of a conventional gravity framing system to the lateral strength of the building. However, since the same moment frame design is used in both the longitudinal and transverse directions of the building, a realistic design would likely employ a combination of weak and strong column orientations. Thus, the two orientations used in this study represent an upper and a lower bound on the lateral contribution of wide-flange gravity columns.

The focus of this study was on "normal-strength" CFT columns that consisted of HSS14 × 14 × 5/16 steel tubes and ASTM A500 Grade B steel with a yield stress, F_y equal to 317 MPa (46 ksi), filled with unreinforced concrete with a compressive strength, f_c' equal to 34.5 MPa (5 ksi). The size of the CFT column and the concrete and steel material specification was selected based on providing a flexural strength equal to 439 kN-m that is comparable, on average, to the flexural strength of the wide-flange columns. For the conventional buildings, most columns at the first story are a W14 × 90 or a W14 × 61. The corresponding design flexural strength of these wide-flange sections about the major axis is equal to 454 kN-m and 778 kN-m, respectively. To investigate the effect of high-strength materials and the effect of geometric properties (thickness, and size), this study included three other types of CFT columns:

- "High-strength" CFT columns consisting of HSS14 × 14 × 5/16 steel tubes and steel with F_y equal to 552 MPa (80 ksi), filled with unreinforced concrete with f_c' equal to 82.7 MPa (12 ksi), and
- "Thick" normal-strength columns: HSS14 × 14 × 5/8 steel tubes and ASTM A500 Grade B steel with F_y equal to 317 MPa (46 ksi), filled with unreinforced concrete with f_c' equal to 34.5 MPa (5 ksi).
- "Large" normal-strength columns: HSS16 × 16 × 5/16 steel tubes and ASTM A500 Grade B steel with F_y equal to 317 MPa (46 ksi), filled with unreinforced concrete with f_c' equal to 34.5 MPa (5 ksi).

It was recognized that high strength concrete, with f_c' greater than or equal to 70 MPa (10 ksi), and high strength steel, with F_y greater than or equal to 525 MPa (76 ksi), are beyond the scope of the AISC 360-16 provisions for composite members (AISC 360-16 section I1.3) [17]. However, recent research [18] examined experimental data from rectangular CFT column tests and conducted parametric studies to address gaps in the experimental data, showing that the axial compressive strength of a rectangular compact high-strength column is predicted with reasonable accuracy by the AISC provisions. Therefore, the high-strength CFT consisting of steel with yield stress equal to 551.6 MPa (80 ksi) and concrete with compressive stress equal to 82.7 MPa (12 ksi) were considered in this study, even though these high-strength materials were not covered by the current AISC provisions.