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Shaking table testing of granite cladding with undercut bolt anchorage

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ABSTRACT

To investigate the seismic performance of granite cladding with undercut bolt anchorage and aluminum connectors, shaking table testing of full-scale specimens was performed. The floor spectrum was constructed and its compatible floor motion time history was generated and used as the input motion. A stiff steel frame was designed to provide the floor earthquake excitation to the cladding specimens installing on its four sides. Experimental results show that the aluminum connectors are the most seismically vulnerable components of the cladding system. The excessive relative in-plane sliding of the two-parts of the aluminum connectors governs the seismic performance of the whole system. While the out-of-plane deformation of the connectors absorbs part of the dynamic energy passed from the steel frame, which reduces the potential damage to the granite panels. The largest component acceleration amplification factor was determined to be about 2.9, which is larger than the recommended values in the current code provisions. Moreover, the experimentally estimated peak bending stress exceeded the design value. Finally, the seismic performance levels of the cladding were quantified and the corresponding fragility curves were also developed.

1. Introduction

Stone panels have been used for many decades in China, US, and the rest of the world to enclose the exterior façade of the buildings. Architects, engineers, and the building occupants benefitted from the stone cladding due to its attractiveness, durability, practicability, and economy. Nowadays, modern technology allows the stone to be manufactured in precise dimensions with thin thickness (20 mm thickness natural stone panels are popular in façade systems), thus provides cost-effective solutions for the fieldstone veneer. Together with some strong anchorage measures, stone claddings are used in many modern building structures, including high-rises and super tall buildings. The structural system of an engineered building typically accounts for only 10–20% of the overall building cost [5]. The amount that the façade contributes to the overall construction cost varies depending on the system chosen, but typically represents another 10–20%, which is almost identical to the building structural system itself. The façade of a tall building is more likely to be at the higher end of this range [35,34], which is an economically significant attribute of the whole building cost.

The use and application of the stone cladding steps ahead of the academic and experimental studies. Consequently, some failure cases of the insufficiently designed and constructed claddings were reported in the literature [20,36]. Moreover, the structural safety problems would be extremely serious once such cladding is installed in a building located in an earthquake prone region. Under severe earthquake excitations, the brittle and heavy panels have high potential of damage and falling off from their original locations causing serious safety threat to the nearby objects and pedestrians [58]. After the 2011 Christchurch earthquake, Baird et al. [7] conducted a survey of 217 multistory buildings in the central business district. Their results indicated that the façade damage was very common where precast cladding panels have fallen down to the ground due to connection failures.

Generally, the stone cladding is a type of nonstructural system attaching to the main building structure. Here, *nonstructural* implies that it should not be designed to contribute to the structural capacity of the main structure. However, irrespective of this design assumption, stone cladding is damaged and transfers some loading to the structural system during earthquake excitations. Except for a few guidelines in building design codes, there is currently a lack of applicable design approaches for designers and engineers to appropriately select cladding details for effective mitigation of earthquake damage. By surveying 25 buildings after the 1985 Mexico earthquake, Goodno et al. [26] stated that improper or inadequate designs of the cladding system are the main causes of their observed damages. Limited studies were conducted to

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investigate the seismic performance of heavy cladding systems where almost all the experimental studies focused on the seismic performance of precast concrete claddings [25,60,24,52]. These experimental results revealed that the connection between the panel and the structural system significantly contributed to the seismic performance and even controlled the seismic response of the main structure [17,48,16,47,49,45,41,29]. Baird [8] studied the force-displacement behavior of a suite of U-shaped flexural mild steel plates (UFPs) for use with reinforced concrete cladding. The full-scale experiments confirmed that UFPs were suitable as low-damage cladding connections by efficiently absorbing the hysteretic energy resulting from the story drift under possible earthquake excitation to the building structure.

To investigate the seismic performance of the artificial stone (Microcrystal glass) cladding with undercut bolt, Lu et al. [38] carried out a shaking table test. The thickness of the panel was only 20 mm and damage of the aluminum alloy connections indicated that more efficient measures should be taken to enhance the load-bearing capacity of the connections. Two full-scale precast concrete cladding panels were tested on a full-scale five-story steel frame building at the E-Defense shaking table facility in Japan and the results showed that the slotted-bolt sliding connection survived the strong 3D earthquake excitations [42]. Besides these tests, two types of façade systems (balloon framing overlaid by stucco and precast concrete cladding) in a full-scale five-story building were tested on the outdoor shaking table at UC-San Diego. Due to the concentration of large interstory drift demands at the lower stories of the tested building, the balloon framed assembly was more severely damaged than the precast concrete cladding [46].

Shaking table tests of granite cladding with undercut bolt connection is rarely reported in the literature. In this paper, the load bearing capacity and seismic performance of such novel cladding system are experimentally investigated. For this purpose, shaking table tests are carried out using floor spectrum-compatible artificial floor motions as the table inputs. The undercut bolt anchorage strength, determination of the input motion and floor acceleration amplification (FAA) factor, and the experimental results are reported in the following sections in detail.

2. Test specimens

Three types of granite stone panels and two types of undercut bolts (Fig. 1). were used in the tests (Table 1). The panels were installed on the four sides of a steel frame (Fig. 2), which was tightly fixed to the shaking table. C-profile (C1-C2) and R-profile (Ear-1), as discussed later, aluminum alloy connectors were hooked on the brackets, which were bolted to the horizontal steel beams.

2.1. Undercut bolt connection

The diameter of the undercut bolt is 6 mm, and its length is 32 mm.

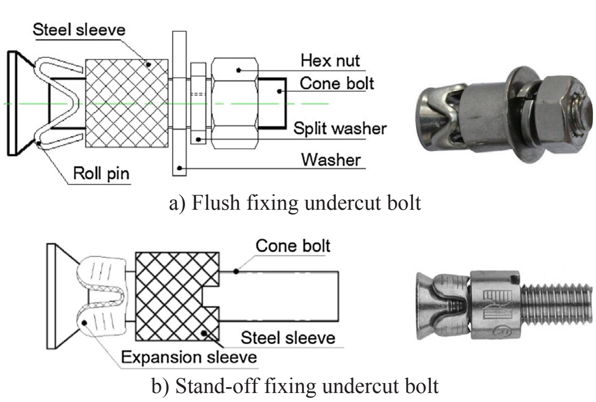

Fig. 1. Undercut bolts.

Table 1
Detailed information of the test specimens.

Side	Stone type [23]	Panel size (mm)	Number of panels	Undercut bolt	Profile bracket
A	G6351	800 × 1500 × 30	5	Stand-off fixing	C1-C2
B	G5622	800 × 1200 × 30	10	Stand-off fixing	Ear-1
C	G6351	800 × 1500 × 30	5	Flush fixing	C1-C2
D	G5153	800 × 1200 × 30	10	Flush fixing	Ear-1

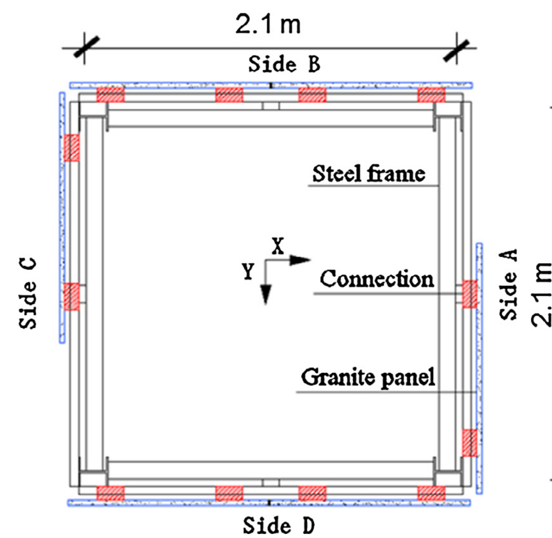

Fig. 2. Plan view of the five-story cladding system.

The washer (including split washer) in the flush fixing undercut bolt (Fig. 1a) ensures that the depth in the panel is sufficiently large to comply with the design requirement, such that the designed anchorage force is guaranteed. There is no corresponding part to the washer (including the split washer) in the stand-off fixing undercut bolt (Fig. 1b). However, the internal surface of the panel becomes flat which makes it convenient to fix the bolt on the support system. The expansion sleeve at the end of the cone bolt (left end of the cone bolt in Fig. 1b) is for mechanical anchorage. This function is enhanced by driving the expansion sleeve against the locking roll pin (Fig. 1a) or the expansion sleeve (Fig. 1b) forcing the anchor to expand within the predrilled hole and thus locking it within the panel.

A typical sectional view of the predrilled hole in the stone panel is shown in Fig. 3. In general, the undrilled depth (t-d_t) should be equal to or greater than 0.4 t where t is the panel thickness. This specification considers the negative wind pressure [11], and the cyclic inertia force acting on the cladding panel. Furthermore, the undrilled thickness

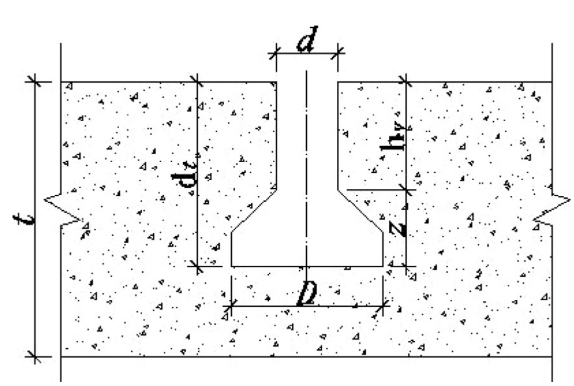

Fig. 3. Typical cross-section view of the undercut drilling in the stone panel.