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Numerical study on the effects of diaphragm stiffness and strength on the seismic response of multi-story modular buildings

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ABSTRACT

Modular building construction relies on prefabricated modules which are assembled onsite to form complete buildings. The assembly requires modules to be connected at discrete locations and results in the formation of discontinuous diaphragms. Diaphragm discontinuities could potentially lead to structural instability or possible diaphragm failure if unaccounted for. Therefore, the primary objective of this study is to evaluate the influence of in-plane diaphragm stiffness and strength on the seismic performance of multi-story modular buildings. A simplified method is presented to establish diaphragm service stiffness considering shear deformation of individual module diaphragms as well as shear and axial deformation of diaphragm connections. This method is used to construct numerical models of a four-by-four bay four-story modular steel building. Three diaphragm stiffness levels, namely rigid, stiff and flexible, are considered for these models and were each subjected to 44 horizontal ground motions relating to seismic events having a return period of 500 years. The results show that increased diaphragm flexibility leads to inter-story drifts that are dramatically large and inertial forces that are considerably different from calculated values using the equivalent lateral force procedure described in current seismic codes. This study is extended further to evaluate performance targets for both elastic and inelastic diaphragm response under a seismic event having a return period of 2500 years. The results are used to propose new seismic design factors, which include force and ductility amplification, and could be implemented for the design of diaphragm connections in multi-story modular buildings.

1. Introduction

1.1. Modular building construction

This study considers modular buildings as those built using prefabricated fully-completed volumetric units called modules, which could be an apartment unit, staircase, structural core component, etc. Such modules are factory manufactured and fit with mechanical connections for assembly on-site, where they would be stacked vertically and scaled horizontally to form complete buildings (see examples in Fig. 1). The key structural materials for modules vary from being timber, concrete or steel; however, steel elements are more commonly used. Vertical structural systems within modular buildings are formed by the assemblage of module frames, whereas horizontal structural systems are formed by the assemblage of module floor and ceiling units. Modular buildings in general have many advantages over traditionally constructed buildings due to off-site manufacturing resulting in reduced construction time, superior quality, efficient material and energy use, reduced environmental impact and improved occupational health and safety [1–10]. It is also believed that modular systems have the potential to address the global demand for infrastructure more effectively than traditional construction techniques [1,5,8].

Despite the many advantages of modular building construction, there are also challenges with regard to technical, logistical and regulatory aspects [5,7,8,11–14]. Logistical issues primarily pertain to the handling, transport and on-site erection whereas regulatory issues pertain to the lack of proper guidelines for design, procurement and overall management. However, the focus is on addressing technical issues and the key technical issues identified relate to the lack of efficient lateral load resistance due to the presence of discontinuous structural systems and the lack of standardised high-performance mechanical connections that can meet the expected performance levels. The presence of discontinuous structural systems is believed to aggravate overall building flexibility impacting lateral load distribution, gravity frame drifts and element force/deformation demands, consequently leading to uneconomical designs and possible collapse or

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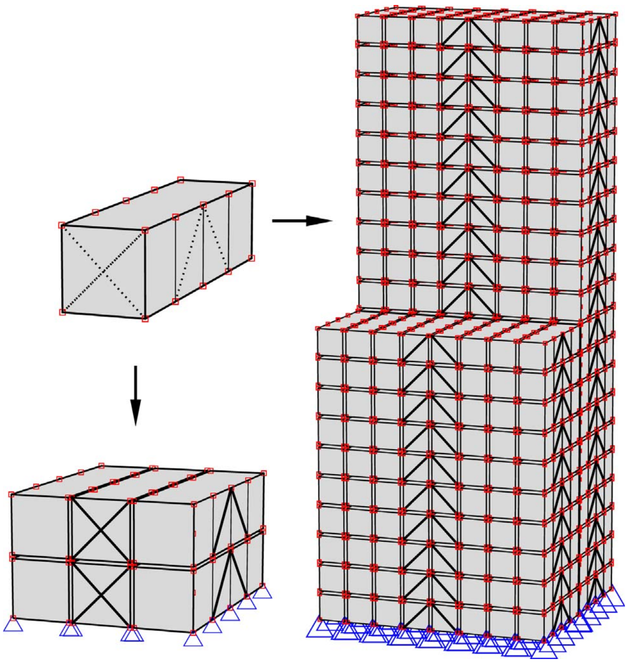

Fig. 1. The versatility of using volumetric modules for building construction.

component failures. Diaphragm discontinuity, in particular, increases diaphragm flexibility and affects the horizontal distribution of lateral loads to the lateral force resisting system (LFRS). Furthermore, higher mode influences are likely to be more significant as well when under the action of seismic loads and current code provisions may not be appropriate for the seismic design of multi-story modular buildings (MSMB). This issue of diaphragm discontinuity in modular buildings has not received much attention when considering recent studies [15–22]. Moreover, for efficient high impact modular building construction and to reap its full benefits, it is expected that fully modular systems (fully independent from traditional on-site construction work) treat modules as black-box entities (internal access to modules is considered to be restricted and inter-module connectivity is established via direct or remote external access only). This further enforces the requirement of high-performance mechanical connections that not only meet stiffness and strength requirements but also be simple in functionality, be remotely operable (not requiring direct external access for manual engagement) and be capable of broad spectrum use. Hence, to assist in the future development of such high-performance mechanical connections, the primary objective of this paper is to establish a simplified method to calibrate diaphragm service stiffness in MSMBs and study the influence of in-plane diaphragm stiffness as well as strength on the seismic performance of MSMBs.

1.2. Behaviour of diaphragms in MSMBs

The diaphragm is a key component that facilitates the transfer of lateral loads to the LFRS and enables the tying of all vertical elements, as well. In conventional buildings of typical form made of concrete or steel (cast in-situ concrete slabs and typically concrete-filled metal decking, respectively), the diaphragms formed therein are idealised as rigid continuous systems if, with no prescribed horizontal irregularities, the span-to-depth ratio is three or less for seismic design and two or less for wind design [23–25]. It is inferable that such idealised rigid continuous diaphragms would not undergo noticeable in-plane deformation, and in the absence of torsional effects, tend to distribute lateral loads based on the relative stiffness of their LFRS [26,27]. However, not all diaphragms fit such a rigid idealisation. Classification of diaphragms, as currently prescribed and as shown in Fig. 2, is based on the ratio between maximum diaphragm displacement relative to the LFRS (Δ_{dia}) and the corresponding average inter-story drift of the LFRS (Δ_{LFRS}). For rigid diaphragm behaviour this ratio is expected to be less than 0.5, for flexible diaphragm behaviour greater than 2.0 and for all values in-between, the diaphragm is classified as stiff [25,28–30]. Diaphragms that are flexible, yet continuous, are treated as simply supported deep beams spanning across the LFRS, where lateral load distribution is approximated by tributary portions of the diaphragm [26,27]. Such flexible diaphragms are likely for MSMBs due to the presence of discontinuities, as a consequence of modularisation (refer to Fig. 1). These discontinuities are likely to reduce diaphragm stiffness affecting the distribution of lateral loads and could aggravate gravity frame drifts. This could potentially cause diaphragm failure, or building instability due to increased second-order effects. Therefore, it is crucial to assess the stiffness of diaphragms in MSMBs so that appropriate measures can be undertaken during design.

1.3. Influence of diaphragms in MSMBs

As mentioned earlier, for idealised rigid diaphragms of typical continuous form, it is generally expected that gravity frames would laterally displace to the same extent of the LFRS. However, the lack of rigidity due to diaphragm discontinuity in MSMBs is likely to result in excessive gravity frame drifts. This likely scenario was faced during the 1994 Northridge earthquake, where many prefabricated garage structures were reported to have partially collapsed due to gravity frame failures as a result of ties connecting prefabricated panels to one another as well as to their LFRS were inadequate to provide for the expected rigid diaphragm action [31]. Furthermore, it has been noted that in typical buildings diaphragm flexibility induces greater participation of higher mode effects, which during the dynamic response, causes out-of-phase diaphragm motions from the LFRS. Building codes do not account for the resulting un-conservative inter-story drifts [32]. Moreover, it is likely that the expected diaphragm design forces for MSMBs could be different from estimates commonly determined through the equivalent lateral force (ELF) methodology. The ELF method prescribes the vertical distribution of the elastic design base shear which is determined by considering regional seismicity factors and structural properties of the selected LFRS type [25,28,29,33]. This methodology is ideally applicable to buildings with low fundamental periods ($T_1 < 0.5s$) and to those that have elastic rigid diaphragms, where the dominant mode shape is analogous to the fundamental vibration mode of a cantilever structure. Analytical studies have also shown the deficiencies in estimating diaphragm inertial forces for low-rise structures with flexible diaphragms through current seismic design methods and have suggested that diaphragms be designed for uniform strength over the entire height of the building to account for large inertial forces that could occur at lower levels [34–37]. This uniform strength design is based on an amplified top level diaphragm design force as determined through the ELF method and has been termed the constant strength design (CSD) approach [34]. In MSMBs, diaphragm discontinuity is likely to increase diaphragm flexibility if connections as well as module floor/ceiling unit stiffness are inadequate. Such a condition of inadequate diaphragm stiffness could potentially lead to diaphragm failure or instability of the structure during seismic events. It is therefore necessary to study the influence of diaphragm stiffness on the seismic response of MSMBs to ensure either a building is designed with diaphragms that are adequately rigid or an appropriate strategy is taken to control the effects of having flexible diaphragms.

1.4. Seismic design of diaphragm connections in MSMBs

The seismic design of structures is governed by assuring basic life safety, yet also achieving economical designs through the allowance of damage accumulation. The accumulation of damage requires the design of buildings for inelastic behaviour. In current practice, this is achieved