
Investigating Options for Simplified Seismic Design of Mixed Systems

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ABSTRACT

Mixed structural systems, which combine distinct lateral load resisting systems in one or more principal directions, are an attractive solution to resist seismic loads. Despite this, mixed systems must be considered carefully during design to recognise the different deformation capacities and hysteretic properties of the individual systems, and account for the effects of displacement compatibility. Diaphragm flexibility can complicate this task further. Means of rationally accounting for these issues is challenging for commonly employed design methodologies, such as the equivalent static or modal response spectrum, as they rely on elastic analysis. This research investigates the accuracy of existing design methodologies for low-rise mixed systems, and trials alternative provision for such methodologies, by way of non-linear response history (NLRH) analysis of a series of case study structures. This paper describes a set of case study buildings examined to date and details the non-linear modelling and analysis approach used to test trial provisions. Preliminary results from NLRH analyses are presented. The results indicate that a simple design methodology can produce satisfactory designs, provided conservative assumptions are made. Concerns arise surrounding the ability of the simplified method to account for semi-rigid roof diaphragm behaviour.

1 INTRODUCTION AND BACKGROUND

Mixed systems are structures which combine multiple distinct lateral load resisting systems (LLRSs) in one or both orthogonal directions. Bruneau and MacRae (2019) and Pascua et al. (2023) reported an increasing trend of novel mixed system structures following the 2010/11 Canterbury earthquakes. Mixed systems may allow designers to exploit the favourable characteristics of each system to create a more efficient structure. Despite increasing popularity, there is a lack of research pertaining specifically to low-rise mixed systems. Nevertheless, there is considerable research investigating Direct-DBD methodologies for mixed systems (Garcia et al. 2010; Sullivan et al. 2006), but DBD may not easily be integrated into force-based codes.

To exploit the advantages of mixed systems, a series of associated challenges must be navigated (Figure 1b). One such challenge is that of displacement compatibility (Figure 1a), by which individual lateral load resisting elements, with different natural displaced shapes, are constrained to displace laterally together.

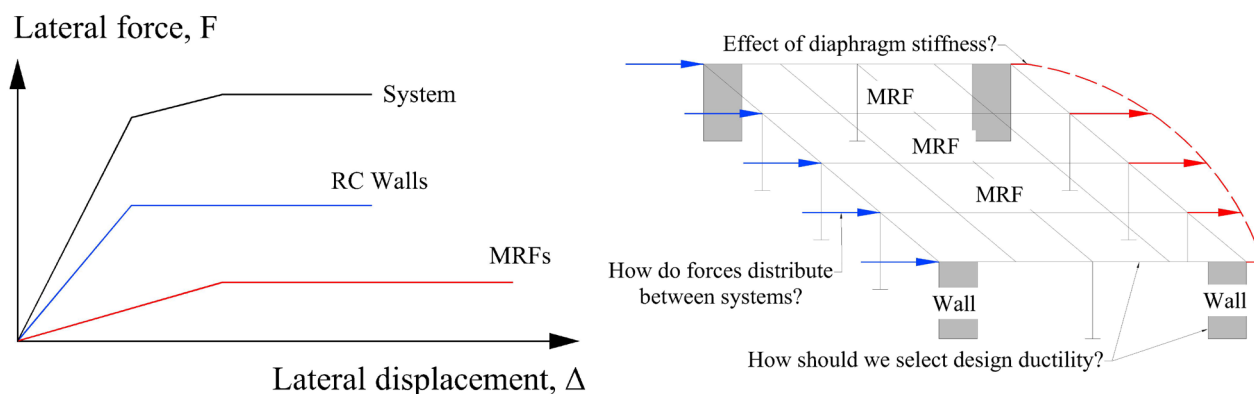


Figure 1: (a) Lateral force-displacement characteristics of a typical mixed system, (b) Common mixed system design challenges.

While it is acknowledged that force-based design is problematic for mixed systems (New Zealand Government 2017), there is limited explicit guidance for the design of mixed systems in the current code. NZS 1170.5 states design should include a rational analysis of the structural system to select a system ductility value and determine the strength proportions of each system. However, there is no specific detail provided on how to go about this process. Appropriately selecting the capacity design hierarchy of a mixed system may also be challenging. The natural tendency of such a system is for elements with high stiffness (such as reinforced concrete (RC) walls) to attract a large portion of the total lateral force. As such, care should be taken to determine capacity design forces at wall-beam/roof connection. However, the member forces may be affected by the LLRS properties, roof diaphragm properties, dynamic effects and inelasticity.

During seismic loading, diaphragm forces are developed from acceleration of the seismic mass of the structure (inertia), and from interaction of the structural elements (transfer). Paulay and Priestley (1992) describe transfer forces as arising from “fighting” between different LLRSs. Gardiner (2011) found transfer forces to be largest when the relative stiffnesses of each LLRS are similar as there tends to be greater resistance from each system to conform to its natural deformed shape. Diaphragm flexibility has been shown to reduce transfer forces and reduce residual diaphragm forces by reducing the extent to which LLRSs are constrained to displace together.

In reality, many roof diaphragms will neither be accurately described as infinitely rigid or fully flexible. For a mixed system, recognition of semi-rigid diaphragm behaviour presents both advantages and challenges. Semi-rigid diaphragms may provide force redistribution between LLRSs in the inelastic range which provides redundancy (Fang 2015; Tremblay et al. 1999). Semi-rigid diaphragms can also be advantageous for mixed systems due to the ability to reduce out-of-phase effects between LLRSs. However, quantification of diaphragm stiffness is uncertain and estimation of internal diaphragm forces is complex, and previous research has shown that equivalent static elastic analyses do not accurately predict diaphragm forces.

2 TRIALLING A SIMPLIFIED EQUIVALENT STATIC METHOD FOR LOW-RISE MIXED SYSTEMS

2.1 Trial procedure

A simple procedure, compatible with the equivalent static method (ESM), has been formulated and applied to a set of initial case study design scenarios for the purpose of method verification. The general process is outlined in Figure 2. As with any ESM procedure, the process may require iteration of member sizes to satisfy strength and stiffness requirements, as well as deformation ductility demand limits.

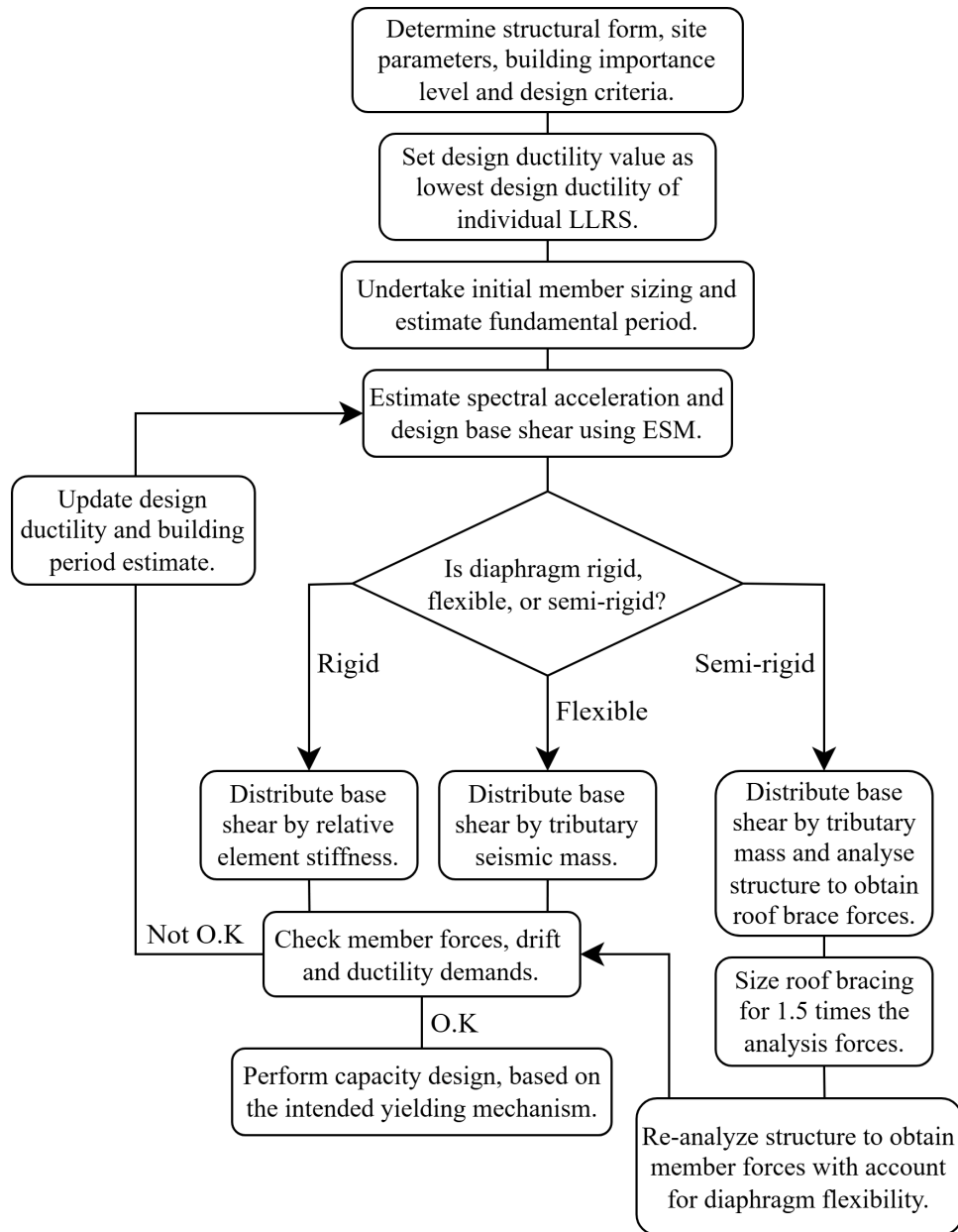


Figure 2: Flowchart of trial equivalent static design procedure for low-rise mixed systems.

As diaphragm stiffness can affect the force distribution and displacement demands between vertical LLRSs, there is significant potential impact of explicitly considering the diaphragm as a semi-rigid diaphragm model. To account for a semi-rigid diaphragm in the elastic design process, SESOC interim design guidance (SESOC 2022) for lightweight roof bracing has been adopted. In line with this, the roof lateral load resisting elements have been designed to resist 1.5 times the elastic actions (with $S_p = 1.0$). Equivalent static forces have been distributed to the roof diaphragm according to Equation 1.

$$F_i = V_b \frac{m_i}{\sum m_i} \quad (1)$$

Where F_i is the force applied at gridline/frame i , m_i is the tributary seismic mass associated with gridline i , and V_b is the design base shear force in the direction being considered. The roof bracing system may then be analysed like a truss to determine the maximum tensile force. As the relative stiffness of vertical LLRSs will affect the magnitude of diaphragm forces, it is important to re-check diaphragm forces after iteration in the design process.

2.2 Case study buildings

The generally typology of the case study structures is a single storey portal frame structure, shown in Figure 3. The structural footprint is 21 m by 45 m, with heights of 7 m and 5 m, on the tall and short sides of the building. The structure comprises three distinct LLRSs; mono-pitched steel portal MRFs spanning in the transverse direction (which are also responsible for supporting gravity loads in the interior bays), precast RC walls located on the two transverse ends of the structure, and steel cross bracing in the longitudinal direction. Structural response in the transverse direction is of primary focus as this is the direction which features a mixed lateral load resisting system. This paper focuses on diaphragm design choices and their implication; therefore the structural form of the three case study structures investigated is identical, with varied roof diaphragm stiffness assumptions of rigid (CS01), flexible (CS02), and semi-rigid (CS03). Key design information is presented in Table 1. The building is assumed to be located in Christchurch and rigid foundations have been assumed. It should be noted that there is a small torsional response observed in the case study structures, owing to stiffness asymmetry in the longitudinal direction cross bracing.

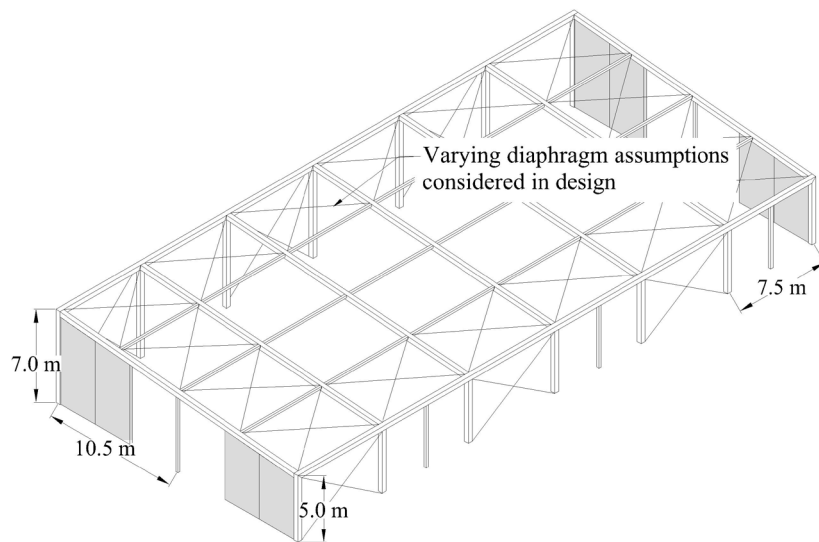


Figure 3: Isometric view of the case study building layout and dimensions.

Table 1: Case study design information (with terminology from TS 1170.5)

Parameter	Weight	Site Class	Importance Level	μ	SLS Drift Limit	ULS Drift Limit	S_p
Value	237.2 T	V	IL2	2.0	0.5 %	2.5%	1.0

2.3 Design results

The equivalent static method design results for the three case study structures are presented in Table 2. It is important to note the capacity design process for the steel MRFs. As the structure has a single storey, a weak-column mechanism has been deemed acceptable and thus the intended mechanism is for yielding at both the base and top of the MRF columns. This allows for more economic column sizing compared with traditional capacity design for a weak-beam mechanism, due to comparatively large beam sizes required to satisfy SLS gravity deflection checks. To satisfy diaphragm stiffness requirements for case study one (rigid), it can be seen that extremely large cross-bracing sizes are required. This finding is consistent with literature that suggests low-rise, slender structures with lightweight roofing may generally not be considered as having a rigid diaphragm. To design such a structure with a rigid diaphragm in reality, a different diaphragm system with much higher inherent stiffness may be required.

Table 2: Case study design results, delineated according to diaphragm.

Diaphragm Scenario	Rigid (CS01)	Flexible (CS02)	Semi-rigid (CS03)
$T_{1,ext}^*$	0.35 s	0.33 s	0.33 s
$T_{1,int}^{**}$		0.76 s	0.52 s
ULS V_b	1118 kN	1067 kN	1118 kN
ULS maximum drift	0.61 %	2.45 %	2.16 %
L_{wall}	3.0 m	3.0 m	3.0 m
t_{wall}	0.1 m	0.1 m	0.1 m
ρ_{wall}	0.75 %	0.37 %	0.53 %
Beam member size	460 UB 67.1	460 UB 82.1	460 UB 67.1
Column member size	200 UC 46.2	250 UC 89.5	200 UC 46.2
Roof X-bracing size	90 mm dia.	-	30 mm dia.
Design governed by	ULS wall moment	ULS drift (in MRFs)	ULS wall moment

* Period of an exterior bay (RC walls). ** Period of an interior bay (Steel MRF).

3 NONLINEAR RESPONSE HISTORY ANALYSIS

3.1 Modelling and analysis approach

3D numerical models of each case study have been produced in *OpenSeesPy* for the purpose of gauging the likely behaviour of the case study building designs via NLRHA. The models utilise a concentrated plasticity approach. The steel portal frames are modelled with elastic beam and column elements, and potential plastic hinge locations positioned at the ends of each element. MRF hinges follow a hysteretic bilinear response based on the modified Ibarra-Medina-Krawinkler deterioration model (Lignos and Krawinkler 2011). The RC walls are modelled with a plastic hinge at the wall base and an elastic cantilever element. The hysteretic behaviour of the RC walls follows the Takeda hysteretic model (Otani 1981). The RC wall top connection to steel framing is assumed to be pinned for initial modelling; however, this connection detail may be investigated at a later date. The foundations are assumed to be rigid. 5% Rayleigh damping is applied to the structure, specified at modes 1 and 3.

The diaphragm modelling process is unique for each of the three case studies. To model a rigid diaphragm, the cross bracing and collector beam stiffness is artificially increased to an extent that the members are effectively rigid. This must be done because the pitched roof precludes the in-built *rigidDiaphragm* command in *OpenSeesPy* from being used. For the flexible diaphragm (CS02), no roof bracing is provided in the transverse direction. The semi-rigid diaphragm (CS03) has been modelling explicitly using design section sizes and probable material properties. In this study, the contribution of roof sheeting and purlins to diaphragm stiffness has been neglected.

Ground motion records are applied bidirectionally with an analysis timestep of 0.005 s. Vertical excitation is excluded from the analysis. Ground motion records have been provided by Sistla and Sullivan (2025), selected in accordance with SESOC guidelines to match the 1 in 500-year return period hazard level, in line with SESOC guidelines (SESOC 2025) from the 2022 New Zealand National Seismic Hazard Model (Bradley et al. 2022).

3.2 NLRHA Results

Figure 4 presents preliminary NLRHA results for the three case study structures, showing the drift profile along the structure, the maximum plastic rotations demands on the RC wall and MRF column bases, and the maximum roof bracing tensile forces for the rigid and semi rigid diaphragm case studies.

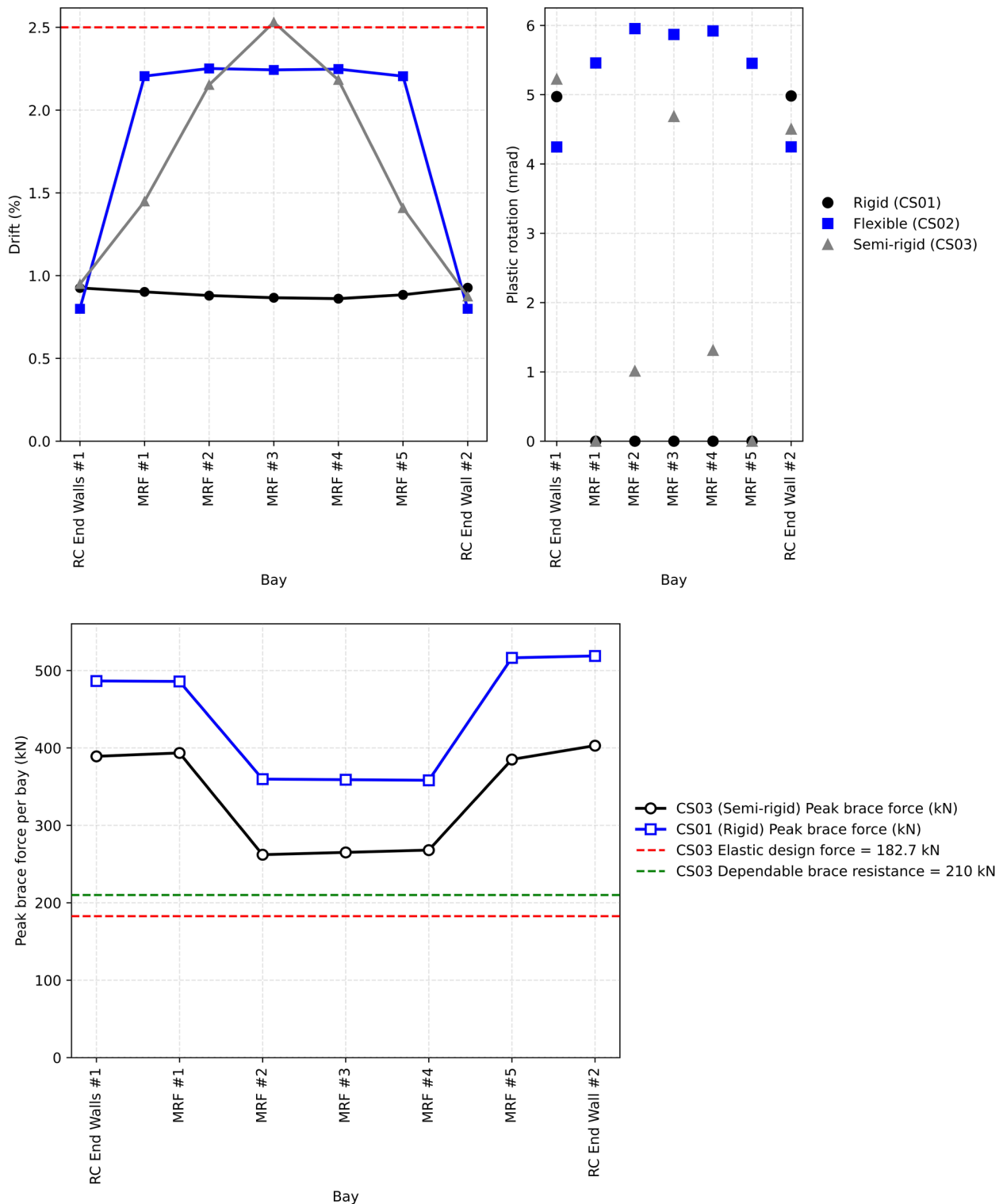


Figure 4: (a) Peak drift profiles, (b) Peak plastic rotations for each LLRS, (c) Maximum roof bracing tensile force for rigid and semi-rigid case studies.

The displacement profiles for each of the three case studies are as expected for the given diaphragm assumptions. For the third case study structure (semi-rigid diaphragm), however, the drift demand in the central portal frame bay exceeded ESM predictions by $\sim 0.5\%$ and slightly exceeded the ULS drift limit of 2.5% . The maximum roof bracing forces recorded for case study three are significantly larger than the design force determined using the trial procedure, and many of the roof braces would be expected to yield during ground excitation. Roof bracing forces were highest in bays adjacent to the RC walls which is consistent with literature findings. It was found that roof bracing force demands were higher for case study one (rigid diaphragm), compared to case study three (semi-rigid diaphragm). This may be attributed to the higher degree of constraint enforced between LLRSs by the rigid diaphragm. Maximum plastic rotation demands in the base of the steel MRF columns were found to be largest in case study two (flexible diaphragm), owing to larger column section sizes which yielded at a lower rotation demand than the other case studies.

4 CONCLUSIONS

A simplified equivalent static design procedure has been trialled for the design of low-rise mixed systems. The design processes show that the presence of a semi-rigid roof diaphragm can significantly affect results, acting to redistribute some force to stiffer lateral load resisting elements whilst also reducing out-of-phase effects between LLRSs. The design process confirmed hypotheses that it may not be practicable to design such this structural typology with a rigid diaphragm when lightweight cross-bracing is employed. 3D non-linear modelling has been undertaken in *OpenSeesPy* to undertake NLRHA to investigate the efficacy of the simplified method and evaluate the effect of diaphragm stiffness. Preliminary NLRHA results were presented which show that for design with a flexible roof diaphragm assumption, the simplified method produces a satisfactory design, provided conservative design assumptions are made. NLRHA highlighted concerns regarding the design of mixed systems with semi-rigid roof diaphragms as large tensile forces and inelastic action was observed in the roof diaphragm bracing, resulting in larger than expected deformation demands. Future research could investigate alternative design provisions for semi-rigid roof diaphragms in low-rise mixed systems, investigate the effect of varied relative stiffness between LLRSs and analyse alternative structure typologies.

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