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Roof Diaphragm Distributed Yielding Concept for Improved Seismic Collapse Performance of Buildings with Rigid Walls/Flexible Roof Diaphragms

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Abstract

Buildings with rigid walls and flexible roof diaphragms (RWFD) are a common type of single-story construction in North America, Europe and New Zealand that incorporate rigid in-plane concrete or masonry walls and flexible in-plane wood or steel roof diaphragms. RWFD buildings have shown poor seismic performance during past earthquake events. In particular, it has been observed that the global seismic response is dominated by the response of the roof diaphragm, which is mainly attributed to large in-plane roof displacements that significantly exceed the displacements of in-plane walls.

The present study explores the concept of distributed yielding in the flexible roof diaphragm by weakening certain intermediate diaphragm zones as a cost effective means to improve the seismic collapse capacity of RWFD buildings and mitigate their seismic vulnerability. A numerical framework was developed specifically for analyzing RWFD buildings and was used to evaluate the proposed concept. Results of nonlinear dynamic time-history response analyses conducted on a typical RWFD building incorporating a wood roof diaphragm show that distributing the inelastic response of the flexible diaphragm along its span is beneficial to the seismic collapse capacity of RWFD buildings. A seismic design approach based on this concept is also formulated and proposed for implementation into the U.S. building codes as an alternative seismic design approach for this type of structure.

Keywords: Seismic design; Collapse performance; Flexible roof diaphragms

1. Introduction

Buildings with Rigid in-plane Walls and Flexible in-plane roof Diaphragms (RWFD) is a common type of single story light industrial construction in North America, Europe and New Zealand. In the United States (US), RWFD buildings represent nearly all warehouse and large big-box retail buildings currently being designed and constructed. RWFD buildings are usually framed with concrete tilt-up wall panels or masonry walls and a roof diaphragm, which can be either wood or steel. In North America, steel deck roof diaphragms are commonly used in Canada, Mexico as well as the United States east of the Rocky Mountains, while west of the Rocky Mountains wood roof diaphragms are the more common construction practice for these buildings.

RWFD buildings have exhibited poor seismic performance during historical earthquake events including the 1964 Alaska, 1989 Loma Prieta, 1994 Northridge, and 2010 and 2011 Christchurch earthquakes [1-3]. Based on observations during past earthquakes, damage at the flexible roof diaphragm was the most dominant failure component for RWFD buildings. It was identified that the damage was mainly concentrated at the roof boundaries resulting from excessive force demands from the out-of-plane wall panels to the diaphragm, where in-plane diaphragm displacements that are considerably larger than the displacements of the in-plane walls. Current U.S. building codes have been revised to address this issue; however, it has been speculated that future failures may now occur in the flexible roof diaphragm [4].

To mitigate the poor seismic performance of RWFD buildings and improve their seismic collapse response, the concept of distributed roof diaphragm yielding is introduced by weakening certain intermediate diaphragm zones below current practice. The efficiency of the proposed concept is explored, in this study, for a typical RWFD building archetype incorporating concrete tilt-up walls and a flexible wood roof diaphragm. Based on the results presented herein, the proposed distributed yielding concept is a cost effective and efficient means of reducing the ductility demands at the roof boundaries, while enhancing the seismic performance of RWFD buildings.

2. Proposed Concept of Roof Diaphragm Distributed Yielding

Based on past earthquake response and analytical studies on RWFD buildings, the main source of inelasticity is expected to be in the flexible in-plane roof diaphragm rather than the rigid in-plane walls [5]. Despite that the current design practices of large roof diaphragms often intentionally reduce the shear capacity towards the center of the roof, the inelastic roof diaphragm behavior remains concentrated towards the roof boundaries. This localized inelastic response results in limited ability to dissipate large amounts of energy and consequently lead to premature building failure.

The approach described in this paper to achieve roof diaphragm distributed yielding is the intentional weakening of certain intermediate roof diaphragm zones below current code based force demands. This approach protects the perimeter roof boundary areas from excessive inelastic demands, while controlling premature roof permanent deformations and building collapse. The proposed concept also offers a cost-effective means of seismic collapse enhancement for RWFD buildings by distributing the inelastic response towards the center of the flexible roof diaphragm and improving the energy dissipation capacity of the building system. An illustrative example of the expected hysteretic response for a typical RWFD building designed per current US practices as well as incorporating the proposed distributed roof diaphragm yielding concept is shown in Fig. 1. It is expected that for a RWFD building incorporating the distributed yielding concept in the roof diaphragm, the inelastic response spreads towards the center of the roof, which leads to reduced ductility demands for the roof diaphragm boundary areas/zones.

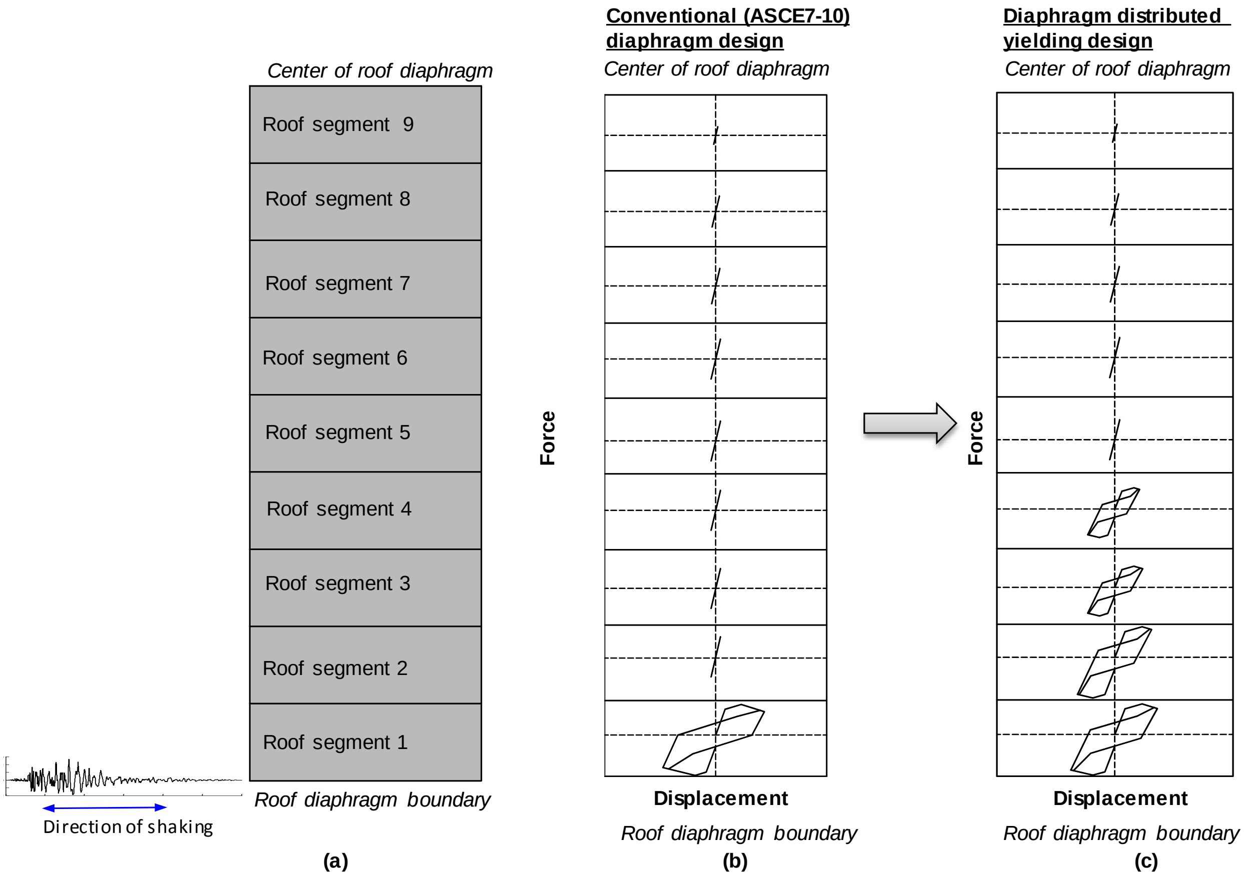


Fig. 1: Expected hysteretic response with: (a) roof discretization, (b) existing design of RWFD buildings and (c) design applying the distributed yielding concept [6, 7]

3. Case Study: RWFD Building Incorporating Wood Roof and Concrete Tilt-up Wall Panels

3.1 Description of Archetype Configuration

A typical single story RWFD building archetype incorporating a 15/32-inch (12mm) wood structural panel (OSB) roof diaphragm and precast concrete tilt-up wall panels was considered to assess the feasibility and efficiency of the proposed concept. The building archetype has plan dimensions 200ftx400ft (60.96m x 121.92m), while the concrete tilt-up wall panels are 30ft (9.1m) tall, 25ft (7.6m) wide and 9.25'' (235mm) thick, incorporating a 3ft (0.91m) tall parapet. A response modification factor (R-factor) equal to 4.0, representing intermediate precast shear walls was used for the conventional design. Current US design code and practices were used for the design, including 2012 IBC [8], ASCE 7-10 [9] and 2008 SDPWS [10] provisions. Seismic Design Category D and Risk Category II were considered in the design. The nailing pattern of the roof diaphragm for the conventional design (see Fig. 2a) was modified to address the distributed roof diaphragm yielding as shown in Fig. 2b. Details of the nailing pattern are included in Table 1.

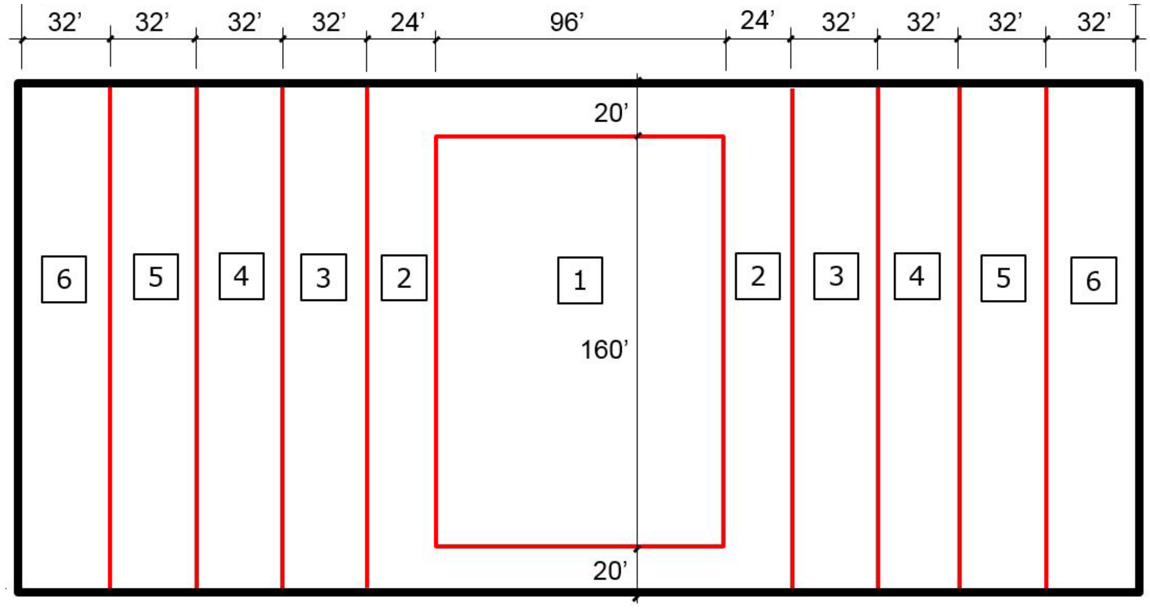
3.2 Description of Numerical Model

A three step numerical framework for the nonlinear dynamic response analyses, introduced by [11] and [6], was used to conduct the collapse evaluation studies of the RWFD building archetype designed with current US provisions as well as those incorporating the proposed roof design concept. An illustration of the numerical framework is shown in Fig. 3. The first step of the framework applied a hysteretic response database of wood roof diaphragm connectors including common nails [7]. The hysteretic parameters of the Wayne-Stewart [12] models were fitted to the connector experimental data to describe the hysteretic response of each connector type. An inelastic roof diaphragm analytical model was developed in MATLAB, in Step 2 of the numerical framework, where each deck panel was modeled as a deep shear beam, and the Wayne-Stewart hysteretic model developed in Step 1 was used to represent the inelastic cyclic response of each roof diaphragm connector. A constant cyclic force applied at the center of the roof was considered for the analysis on the diaphragm model to induce constant shear forces in the roof. The total in-plane flexible roof diaphragm displacement, as schematically illustrated in Fig. 4, was computed as the sum of: (i) the elastic shear deformation of each individual panel, (ii) the inelastic deformations (slippage) of connectors and (iii) the elastic flexural deformations of the chord members. In the last step of the numerical framework, a two dimensional building model was generated in the general-purpose RUAUMOKO2D software [13], representing the three dimensional building without accounting for torsion. The building model considers the in-plane and out-of-plane vertical wall responses, the second order (P-Δ) effects and the in-plane diaphragm springs developed in the second phase to account for the global hysteretic roof diaphragm response. The inelastic horizontal roof spring elements were modeled at locations coinciding with the centerline of the out-of-plane wall panels. The elastic flexure and shear response of the in-plane wall panels was modeled by a single horizontal elastic spring, while vertical beam elements simply supported at the top and bottom with four masses lumped along their height were considered to model the out-of-plane walls. Note that the wall-to-diaphragm connections were assumed rigid in the modeling. A low value of initial stiffness Rayleigh damping equal to 2% of critical was selected as a representative value for RWFD buildings that include fewer nonstructural components than do conventional frame-and-wall buildings, while minimizing potential damping ratio overshoots that could occur as a result of the initial stiffness proportional damping formulation during yielding of the system.

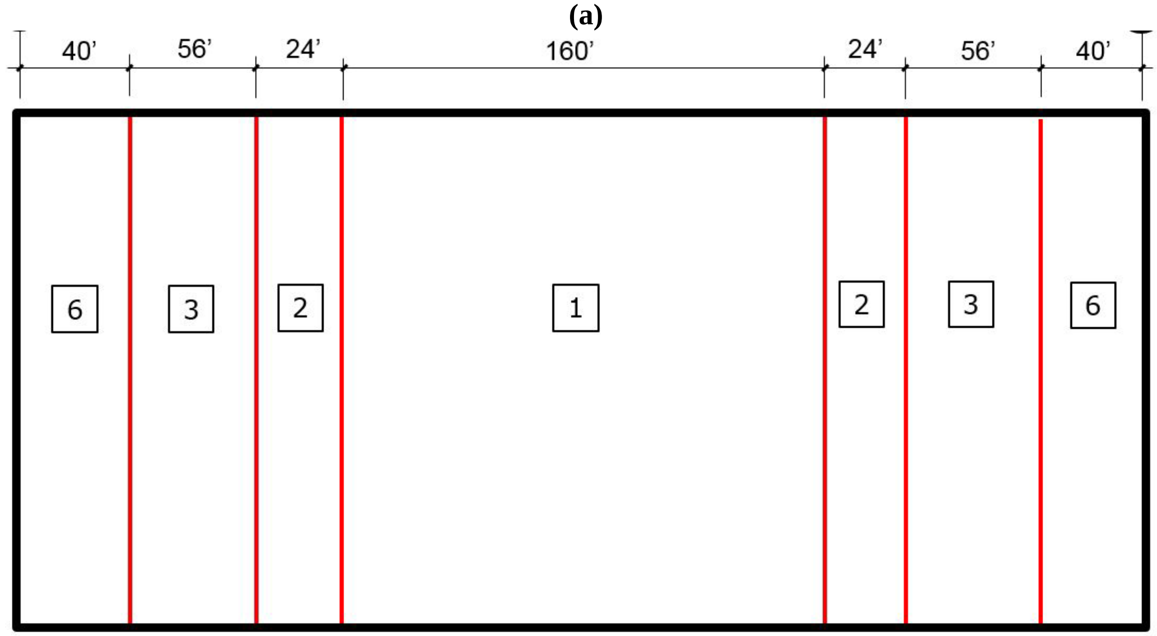
Steps 2 and 3 of the numerical framework were validated with analytical and experimental studies available in the literature [6], while a parametric study was conducted to finalize certain modeling parameters [11].

Table 1: Diaphragm Nailing Zones (1 in = 25.4mm)

Sheathing type: 15/32” Structural I OSB Sheathing Connector type: 10d nails (0.148” diameter x 2” long)				
Zone	Framing Width at Adjoining Edges	Lines of Nails	Nailing per line at Boundary & Continuous Edges	Nailing per line at Other Edges
1	2x	1	6” o.c.	6” o.c.
2	2x	1	4” o.c.	6” o.c.
3	2x	1	2.5” o.c.	4” o.c.
4	3x	1	2” o.c.	3” o.c.
5	4x	2	2.5” o.c.	4” o.c.
6	4x	2	2.5” o.c.	3” o.c.



(a)



(b)

Fig. 2: Roof diaphragm nailing details for: (a) existing/conventional design of RWFD buildings and (b) design applying the distributed yielding concept (1ft=0.3048m)

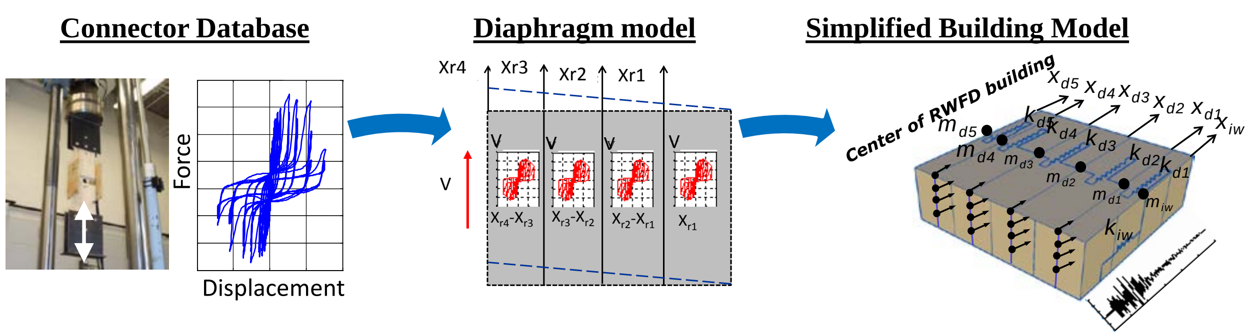


Fig. 3: Three step sub-structuring numerical framework

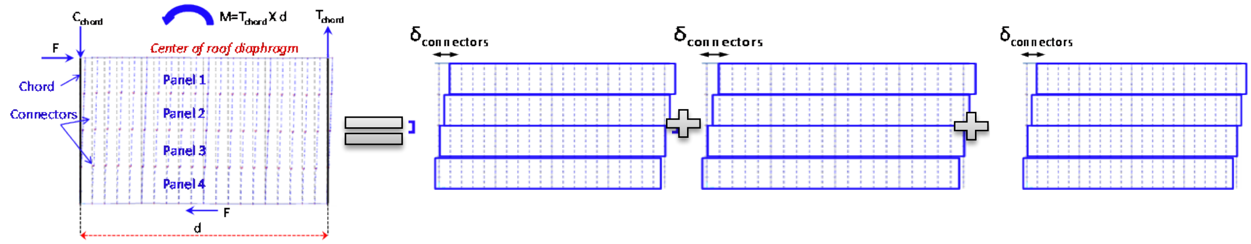


Fig. 4: Illustrative representation of the analytical inelastic roof diaphragm model developed in MATLAB

3.3 Response Analysis Findings

In this section the response analysis results are presented for the case study building archetype incorporating both designs including its dynamic properties characterization as well as non-linear response.

3.3.1 Dynamic Properties

Eigenvalue analyses were conducted for the building archetype, incorporating both conventional design as well as distributed yielding concept, to evaluate its natural periods of vibration and respective mode shapes. The fundamental mode shapes for both designs for seismic excitation in the short and long building direction are presented in Fig. 5 and Fig. 6, respectively. Adopting the proposed yielding concept in the roof diaphragm design has minor effect on the building's mode shapes and fundamental period. The fundamental period increase of approximately 8% and 14% is observed for shaking along the short and long directions, respectively. Moreover, the fundamental period used for the design per ASCE 7-10 is equal to 0.26 sec, computed per Eq. 1, which is considerably shorter than the measured period in both directions during the analyses. The fundamental period of the building is underestimated by 69% and 47% for excitation along the short and long directions, respectively.

$$T=0.02h^{0.75}=0.26 \text{ sec} \tag{1}$$

where, h is the building height in ft (30 ft=9.1m)

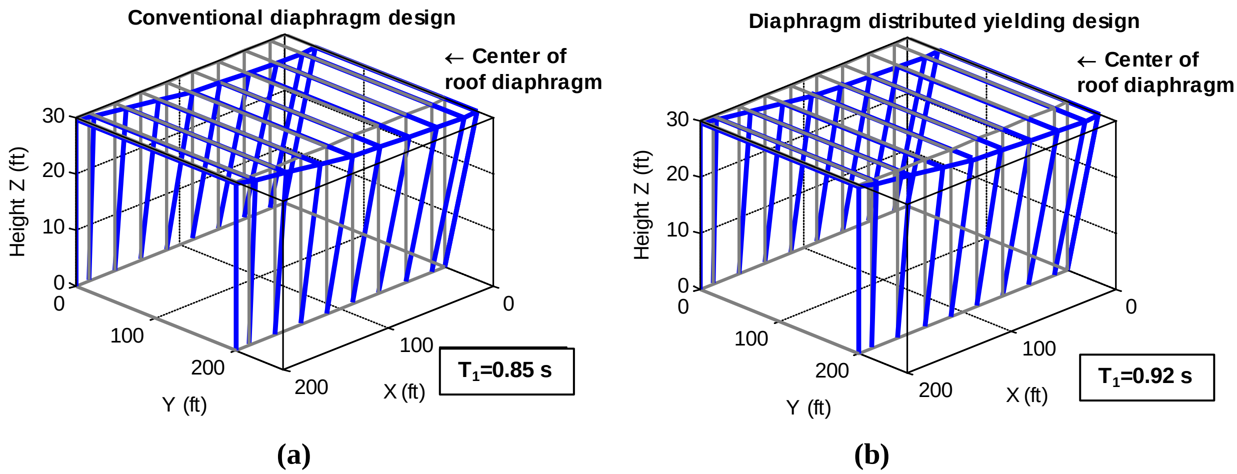
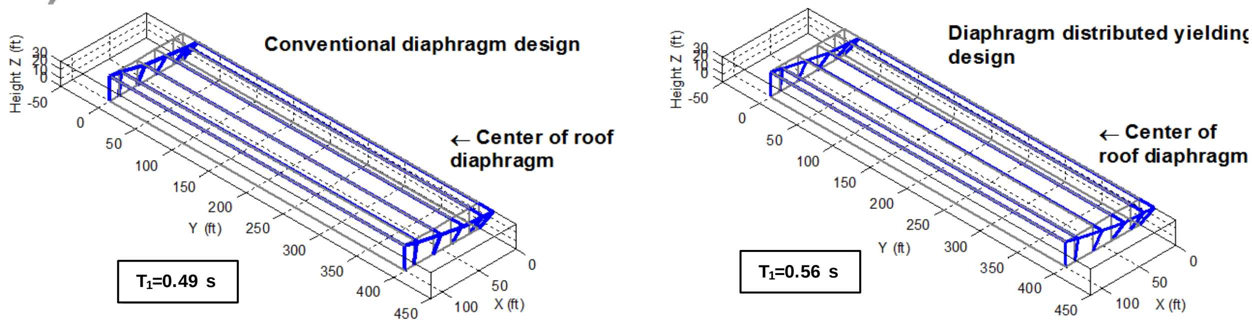


Fig. 5: Fundamental mode shape and respective period for shaking along the short direction: (a) conventional (ASCE 7-10) diaphragm design and (b) diaphragm distributed yielding design (displacement amplification factor=40; 1ft=0.3048m)

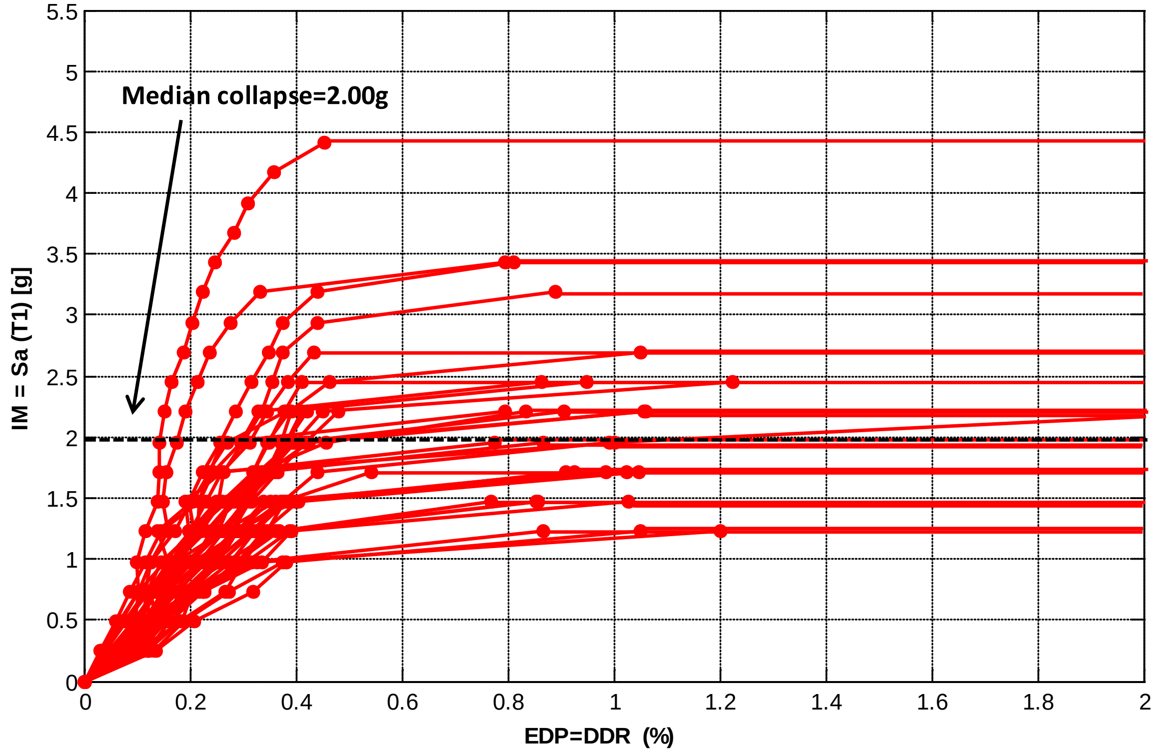


(a) (b)

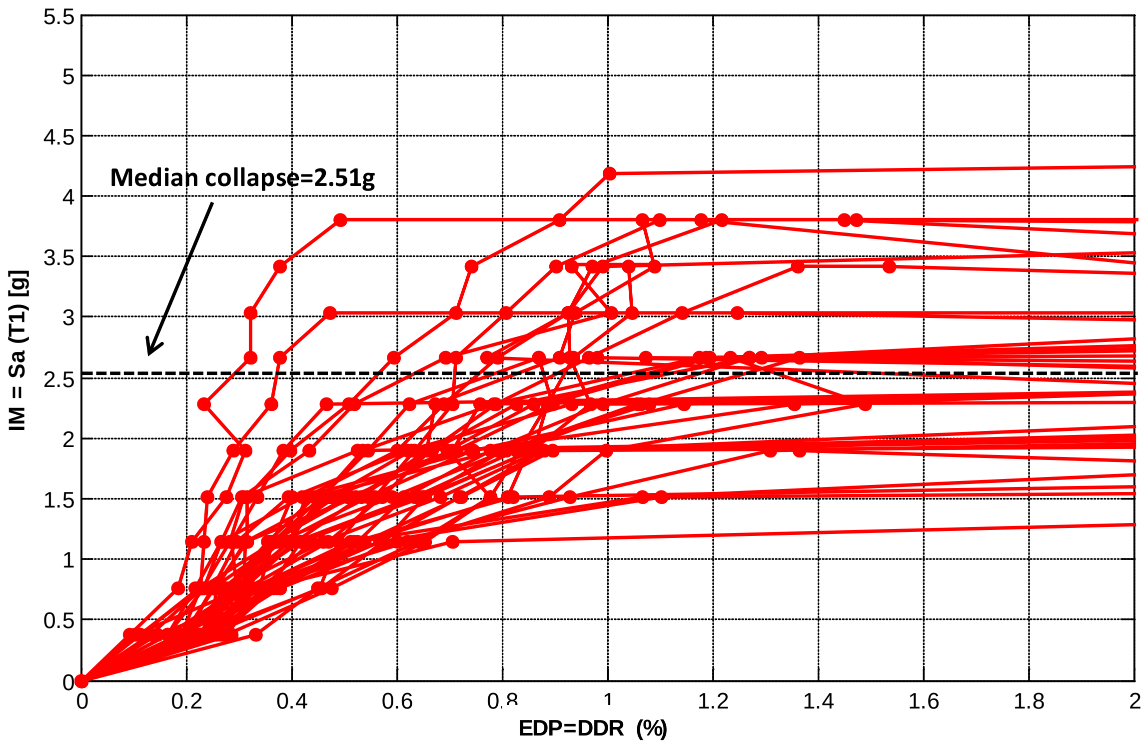
Fig. 6: Fundamental mode shape and respective period for shaking along the long direction: (a) conventional (ASCE 7-10) diaphragm design and (b) diaphragm distributed yielding design (displacement amplification factor=20; 1ft=0.3048m)

3.3.2 Non-linear Time History Analyses Response

Non-linear time history analyses were conducted using the FEMA P695 far-field ground motion ensemble [14] to conduct Incremental Dynamic Analyses (IDAs) [15] and evaluate the collapse response of the building incorporating the proposed yielding concept. The IDA results are presented for excitation along short and long directions incorporating both designs for the roof diaphragm in Fig. 7 and Fig. 8, respectively. From the IDAs the median collapse intensity was computed for each building design. The median collapse intensity is defined, in this study, as the median 2% damped spectral acceleration at the fundamental period of the building for which 50% of the ground motions causes its sidesway collapse. Considering the IDA results, collapse fragility curves were generated for both roof designs and are presented in Fig. 9. The spectral acceleration at the fundamental period of the building with the conventional design was considered as the Intensity Measure (IM) for this collapse study to produce the fragility curves. This approach was followed in order to compare the collapse performance of the RWFD building archetype under the same fundamental period. The roof diaphragm drift ratio (*DDR*), defined as the displacement at the center of the roof divided by half the roof length, was used as the Engineering Demand Parameter (EDP). It is observed that the collapse performance of the RWFD building archetype is improved when the distributed yielding concept is implemented in the roof design for shaking in both directions associated with increase of the median collapse capacity by 25% and 10% for short and long direction excitation, respectively.

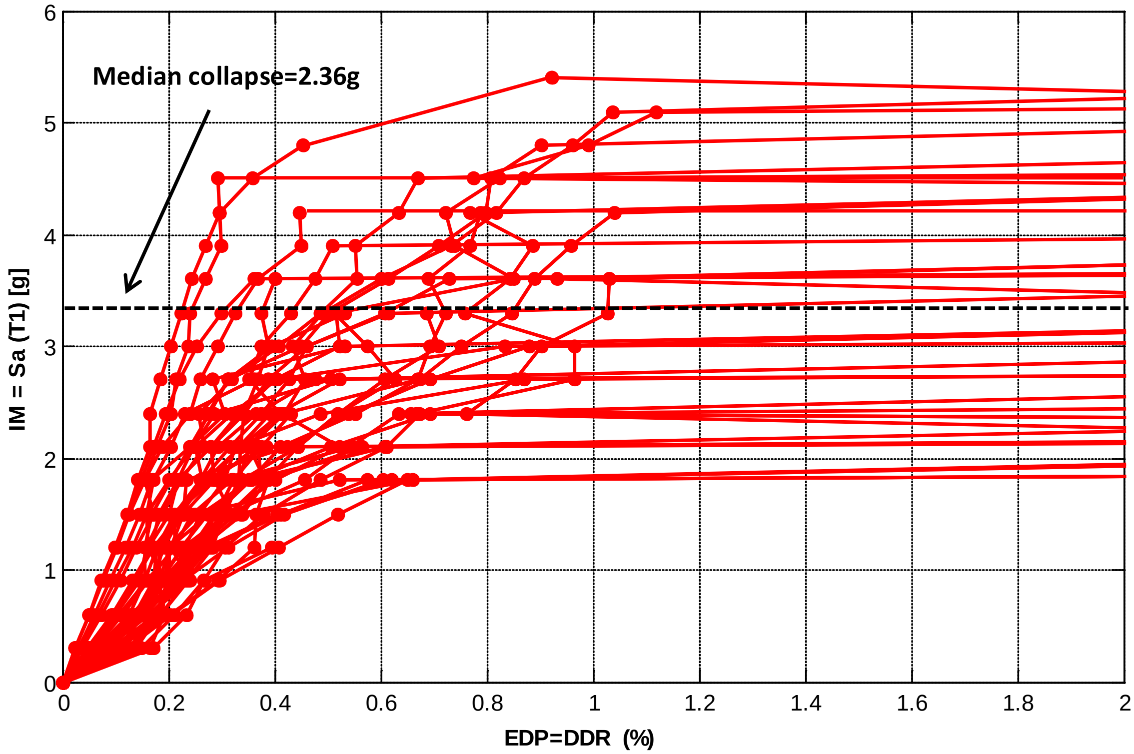


(a)

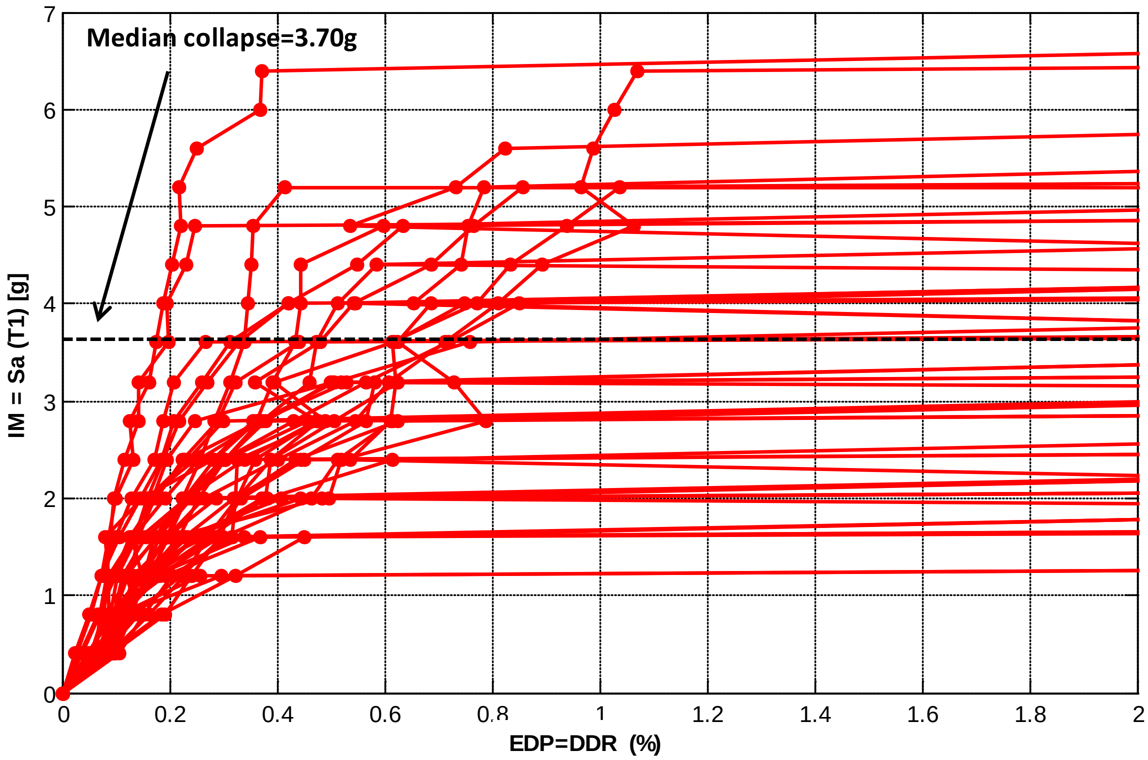


(b)

Fig. 7: IDA results for short direction excitation (a) conventional (ASCE 7-10) diaphragm design and (b) distributed yielding roof diaphragm design

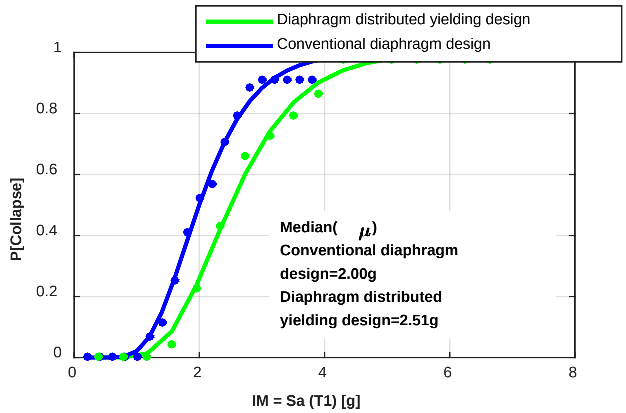


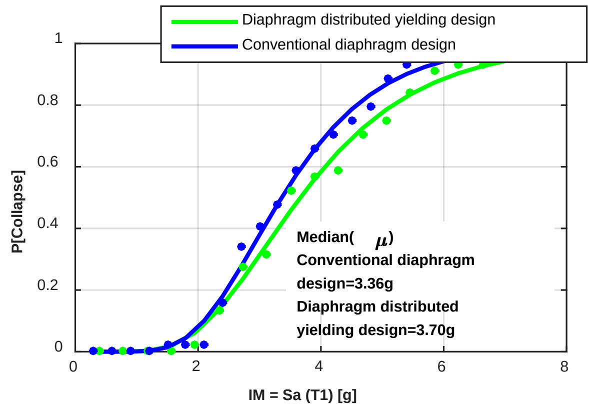
(a)



(b)

Fig. 8: IDA results for long direction excitation (a) conventional (ASCE 7-10) diaphragm design and (b) distributed yielding roof diaphragm design

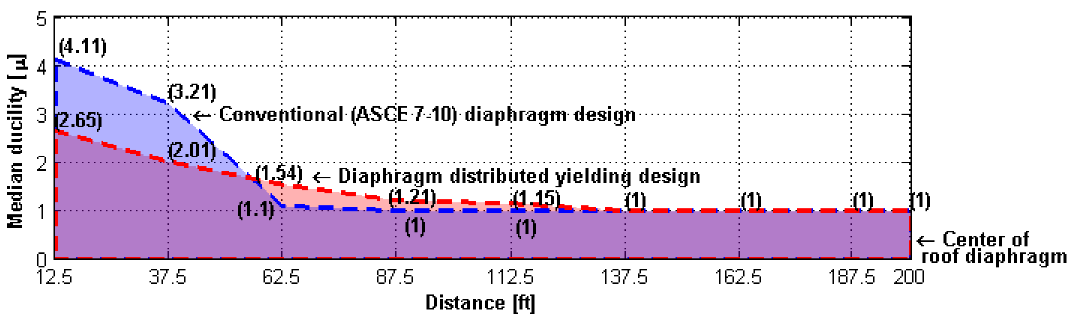




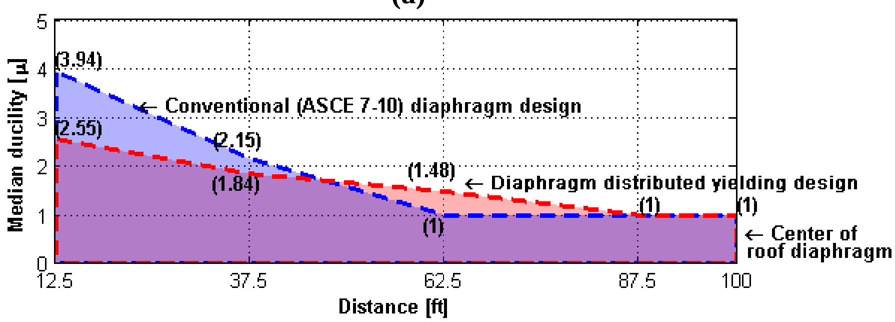
(a) **(b)**

Fig. 9: Collapse fragility curves for conventional (ASCE 7-10) and distributed yielding diaphragm design: (a) short direction excitation and (b) long direction excitation

To better demonstrate the efficiency of the proposed roof diaphragm distributed yielding concept, the ductility at Maximum Considered Earthquake (MCE) intensity was computed for short and long direction excitation and is presented in Fig. 10. It is observed that the MCE ductility is more evenly distributed along the roof diaphragm span for the building archetype incorporating the proposed concept in both directions of shaking.



(a)



(b)

Fig. 10: Median ductility distribution using the FEMA P695 ground motions at MCE intensity level for: (a) short direction excitation and (b) long direction excitation (1ft=0.3048m)

4. Proposed Seismic Design Methodology

A design methodology based on the proposed roof diaphragm distributed yielding concept for RWFD buildings has been proposed by [16] and [17]. The proposed methodology introduces a response modification for the design of the roof (R_{dia}) along with a separate R-factor that is currently used in U.S. seismic provisions for the design of the vertical elements of the seismic force resisting system (SFRS). Furthermore, an amplification factor for the roof shear forces for a certain distance of the diaphragm span from both side edges is introduced to ensure distributed yielding of the roof diaphragm. An R_{dia} of 4.5 was proposed to be used along with an amplification factor of 1.5 for the roof shear forces for a distance of 10% of the diaphragm span from both side edges, as schematically shown in Fig. 11.

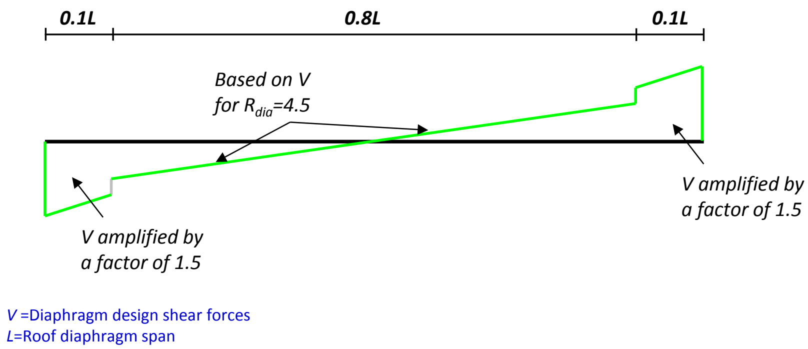


Fig. 11: Roof diaphragm design shear forces for proposed seismic design approach to ensure distributed roof diaphragm yielding [16]

5. Summary and Conclusions

A new design concept for RWFD buildings based on distributed roof yielding was introduced as a means to improve their seismic collapse capacity and mitigate their seismic vulnerability. It is proposed that the distributed roof diaphragm yielding is achieved by strategically weakening certain intermediate roof zones below current code-based force demands. The efficiency of the proposed design concept was numerically accessed for a building archetype incorporating wood roof diaphragm and concrete tilt-up wall panels. Based on the results of this study, an improved collapse capacity of the RWFD building archetype is obtained when the proposed concept is adopted in the diaphragm design. Furthermore, a better displacement ductility distribution along the roof span is achieved leading to less damage at the boundaries of the roof. The proposed distributed yielding concept was used to develop a force-based design methodology introducing an R-factor for the design of the roof along with an amplification factor for specified end lengths of the roof.

6. Acknowledgements

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