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A NONLINEAR STATIC PROCEDURE FOR THE TSUNAMI DESIGN OF A REINFORCED CONCRETE BUILDING TO THE ASCE 7 STANDARD

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Abstract: *New ASCE 7-16 Chapter 6 offer a comprehensive and practical methodology for the design of structures for tsunami loads and effects. While they provide prescriptive tsunami loading and design requirements, they also allow for the use of performance-based analysis tools. However, no guidance is provided as to how the performance-based analysis should be performed. This paper presents an improved nonlinear static pushover procedure for the assessment of the nonlinear capacity of structures to tsunami, within the framework of the ASCE 7-16 provisions. For this purpose, a prototypical reinforced concrete multi-storey building exposed to high tsunami hazard in the US Northwest Pacific coast is assessed. This is a building with sufficient height to provide last-resort refuge for people having insufficient time to evacuate outside the inundation zone. Two different tsunami load discretisation methods are applied to investigate the structural capacity under tsunami systemic and component loading, respectively. The results of the nonlinear static pushover analyses show that the structural system has sufficient lateral strength to resist ASCE 7-16 prescribed tsunami loads. However, when component-based loading is considered, the seaward ground storey columns are observed to fail in shear, precipitating structural failure. This is in agreement with the ASCE 7-16 simplified systemic acceptance criteria, i.e. that the structure is unsafe for use as a refuge, and that it would require significant strengthening. However, the use of the VDPO provides information of what needs to be strengthened in order to improve the tsunami performance of the structure.*

Introduction

The catastrophic effects of recent tsunami triggered by large subduction earthquakes in the Indian Ocean (2004) and Japan (2011) highlighted the threat that many coastal communities in the US Pacific Northwest are exposed to. It has been established that this coastal region is at high risk of being hit by a destructive tsunami following a Mw 9 earthquake generated along the Cascadia subduction zone (Atwater et al., 1991; Yeats, 2015; Goldfinger et al., 2017).

In 2016, a new Chapter 6, "Tsunami Loads and Effects" in ASCE 7 Standard, *Minimum Design Loads and Associated Criteria for Buildings and Other Structures* (ASCE, 2017), became the world's first comprehensive tsunami design building code. ASCE 7-16 tsunami design provisions have been included in the requirements of the 2018 International Building Code (IBC), and an extensive guide of these with example applications is now available in Robertson (2019). The main steps for the design of buildings to ASCE 7-16 tsunami design provisions are outlined in Figure 1. For critical buildings within the mapped Tsunami Design Zone (TDZ), ASCE7-16 defines load and design requirements. In particular, prescriptive acceptance criteria are defined for evaluating both systemic and component response of the structure. The code allows for the use of performance-based criteria, which include nonlinear static analysis. However, no detailed guidance is provided as to how these performance-based methods should be performed.

Performance-based design of structures for tsunami is much less developed than for other natural hazards, such as earthquakes. This is due to the complexity of understanding the interaction of tsunami with structures and the challenges related to developing numerical models that can simulate realistic tsunami loading and capture the resulting building damage mechanisms

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(Rossetto et al. 2018). Thanks to recent advances in physical modelling of tsunami and new field observations from tsunami reconnaissance missions, enhanced relationships for estimating tsunami loading and new structural analysis approaches have been established. Macabuag et al. (2014) performed nonlinear static pushover analysis to assess the structural response of a simple reinforced concrete frame under different code-based tsunami loadings, including those prescribed by ASCE 7-16. For instance, hydrodynamic forces were applied assuming a constant tsunami inundation depth and modelled using a lateral distribution of loads applied at each storey along the seaward columns. This approach, herein referred to as constant depth pushover (CDPO), is similar to a seismic pushover analysis, since the lateral tsunami force distribution is increased monotonically. Hence, this approach can be easily implemented in most structural analysis software. CDPO analyses have been employed to perform fragility assessment studies of a steel frame (Attary et al., 2017) and a reinforced concrete (RC) school (Alam et al., 2018).

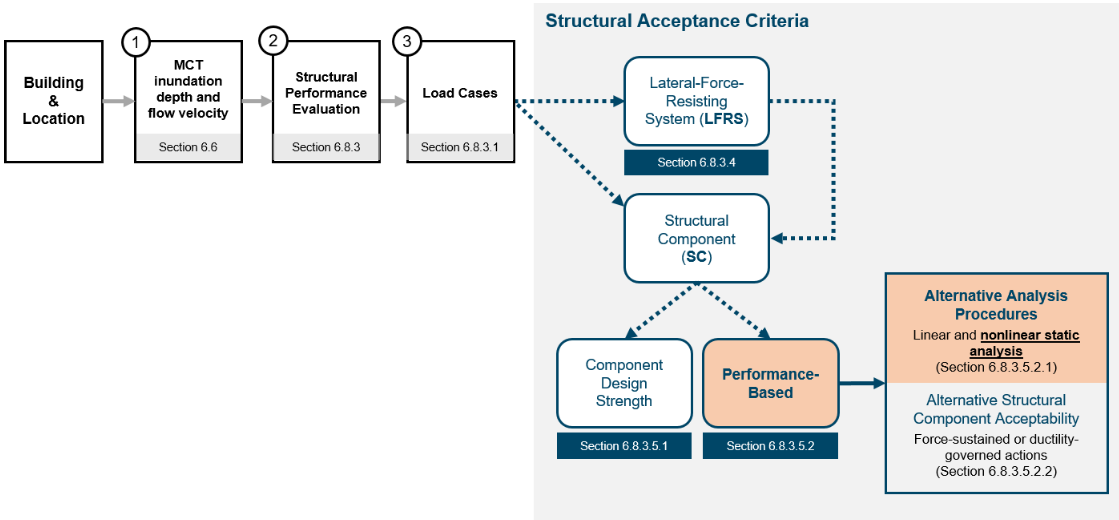

Figure 1. Tsunami nonlinear static analysis within the framework of ASCE 7-16 tsunami design provisions.

To assess the tsunami fragility of a Japanese RC building designated as tsunami evacuation centre, Petrone et al. (2017) developed novel analysis approaches, namely time-history dynamic analysis and variable height pushover. The latter is referred to in this paper as variable depth pushover (VDPO). The tsunami time-history procedure follows the same principles of a seismic time-history analysis, apart from the input data, which is the tsunami force estimated from a simulated inundation time-history. In a VDPO, the tsunami inundation depth at the site of the structure monotonically increases, while the flow velocity is calculated assuming a constant Froude number. For all methods, the estimation of the tsunami hydrodynamic force was based on experimentally-validated equations by Qi et al. (2014), which account for the regime conditions of the flow impacting the structure and the density of the urban environment. In Petrone et al. (2017), comparison of the results of time-history, VDPO analysis and CDPO analysis highlight that, in terms of engineering demand parameters, (i.e. inter-storey drifts and column shear forces), VDPO is in good agreement with the dynamic analysis, and consistently more accurate than CDPO. However, being a load-control analysis, VDPO is not capable of capturing any degrading branch in the pushover curve. This issue is overcome by the improved VDPO proposed in Baiguera et al. (2019). The improved VDPO was adopted in the systemic response assessment of a prototypical RC frame in a TDZ, using different loading assumptions. This paper extends the analysis methodology presented in Baiguera et al. (2019) to include a new component loading approach. The results of this assessment are compared to the prescriptive acceptance criteria of the ASCE 7-16 provisions.

Tsunami hydrodynamic forces on buildings

The ASCE 7-16 Chapter 6 provides a practical methodology to calculate the overall tsunami load on a structure (F_T), which is estimated using the following hydrodynamic drag equation (ASCE, 2017):

$$F_T = \frac{1}{2}\rho_S I_{tsu} C_d C_{cx} B(hu^2) \quad (1)$$

where ρ_S is the fluid mass density, I_{tsu} is the importance factor for tsunami forces (= 1.0 for TRC II), C_d is the drag coefficient based on the ratio B/h [Table 6.10-1 in ASCE (2017)], B is the building width, h is the inundation depth, u is the flow velocity, and C_{cx} is the proportional closure coefficient (with a minimum value of 0.7, adopted in this study). The tsunami depth and flow velocity (h and u) vary according to time-history curves that are normalised to the maximum values at the building site. The maximum inundation depth h_{max} and flow velocity u_{max} are determined by applying the Energy Grade Line analysis (Kriebel et al., 2017). Figure 2 shows the tsunami time-history curves for the case-study building presented later in this paper. It can be seen that the maximum lateral hydrodynamic force on the structure occurs when the velocity reach its peak in each direction and the inundation depth is 2/3 of h_{max}. This is the most critical stage, indicated as Load Case 2 (LC2) in the provisions.

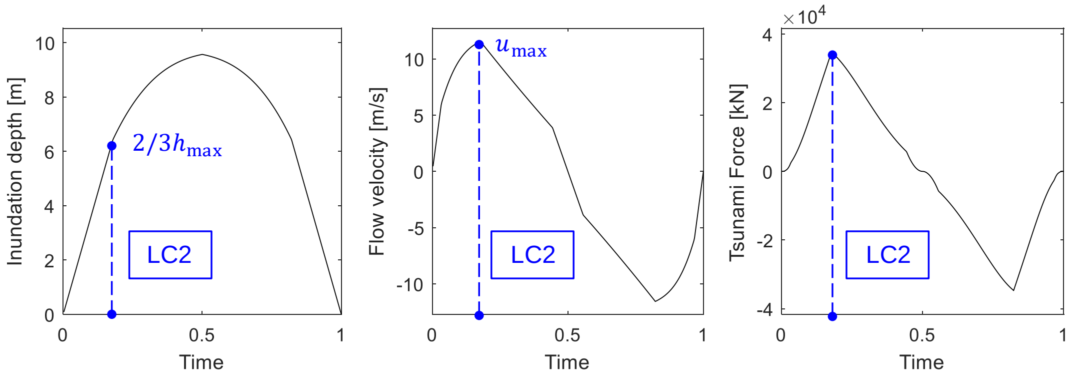

Figure 2: Tsunami inundation depth, flow velocity and force time-history curves at the building site in Seaside.

Nonlinear Pushover Analysis Procedures

The design methodology of ASCE 7-16 provisions, illustrated in Figure 1, allows for the use of alternative performance-based criteria to check the design of structural components. This includes the adaptation of nonlinear static pushover analysis of ASCE 41-13 (ASCE, 2014) to tsunami loading. The objective of this paper is to present a methodology whereby nonlinear static pushover analysis can be applied for tsunami assessment of buildings located in the TDZ, following the ASCE 7-16 provisions.

Analysis Procedures

The improved VDPO consists of a two-phase analysis procedure. In Phase 1, a load-control pushover analysis is conducted assuming an inundation depth that increases at each time step in a pseudo-time domain. In Phase 2, the analysis switches to response-control, where the displacement is incremented, and the corresponding tsunami force is calculated assuming the same inundation depth (and load pattern) as in the last step of Phase 1 of the analysis. The switch from Phase 1 to 2 occurs when the analysis encounters a numerical convergence issue. Once this occurs, Phase 1 analysis is repeated up to the time step preceding the numerical issue, and then Phase 2 is initiated.

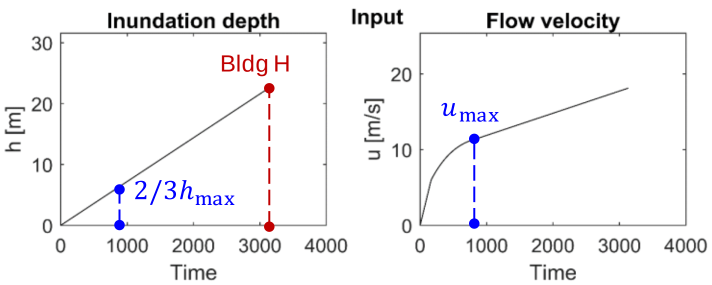

Figure 3: Inundation depth and flow velocity time histories for Phase 1.

For the application of the VDPO in this paper, Phase 1 applies a tsunami force in accordance with the ASCE 7-16 inundation depth and flow velocity time histories up to LC2; if no numerical convergence is encountered, Phase 1 continues with linearly increasing inundation depth and flow velocity, as shown in Figure 3. Throughout Phase 1 and 2 of the analysis, the tsunami hydrodynamic force on the structure is estimated according to Equation 1, which accounts for a varying C_D dependent on B/h.

Loading distributions

ASCE 7-16 provisions assume that the hydrodynamic load pressure distribution on the building is uniform. Different methods can be applied for distributing the hydrodynamic load pressure over the height of the building. A typical approach used in past studies is to apply the loads at each storey level (S). The tsunami forces are calculated using a simple influence area approach, as illustrated in Figure 4 (left). This approach is in agreement with the ASCE 7-16 provisions.

As illustrated in Figure 1, the ASCE 7-16 design methodology requires that every structural element should be evaluated for component loads. A bespoke loading distribution is proposed in this study. This approach consists in allocating a portion of the total base shear directly to the columns on the front of the building and applying the lateral load at 6 points along each column height (see Figure 4 right). This "distributed" load discretisation is the one recommended in Petrone et al. (2017), which they show to provide the best estimation of demand parameters. To evaluate the impact of systemic and component loads in one single analysis, an increased drag component force (e.g., C_d = 2 for square columns) is applied on a single exterior column, while redistributing the overall tsunami force to the remaining columns on the front of the building. For the selected exterior column, the component loads include hydrodynamic drag with debris damming effects and debris impact loading, as per the ASCE 7-16 provisions.

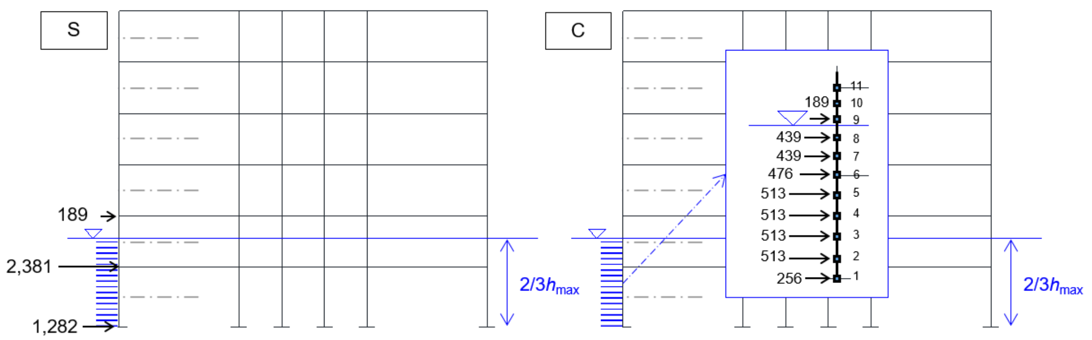

Figure 4: Loading discretisation methods S (left) and C (right).

Case-study building

Prototype building

A six-storey office building is considered as a case-study (Figure 5). The building is located in Seaside, Oregon, which is very close to the Cascadia subduction zone and thus characterised by high seismic and tsunami hazards. Figure 6 illustrates the building location within the 2,500-year probabilistic tsunami design zone map of Seaside. Based on the EGLA conducted in McKamey & Robertson (2019), h_max and u_max at the building site are 9.57 m and 11.56 m/s, respectively.

The structure is classified as Tsunami Risk Category (TRC) II, and therefore it is not subject to tsunami provisions. However, the ASCE 7-16 encourage local jurisdictions to require tsunami design for tall TRC II buildings, to provide effective secondary alternative refuge. Chock et al. (2018) established suitable height thresholds for communities throughout the US Pacific coast, satisfying both the prescriptive acceptance criteria and a recommended height at least 3.66 m greater than the inundation depth. It can be seen that the upper three stories of the building are above h_max, i.e., they could function as a refuge according to the proposal of Chock et al. (2018).

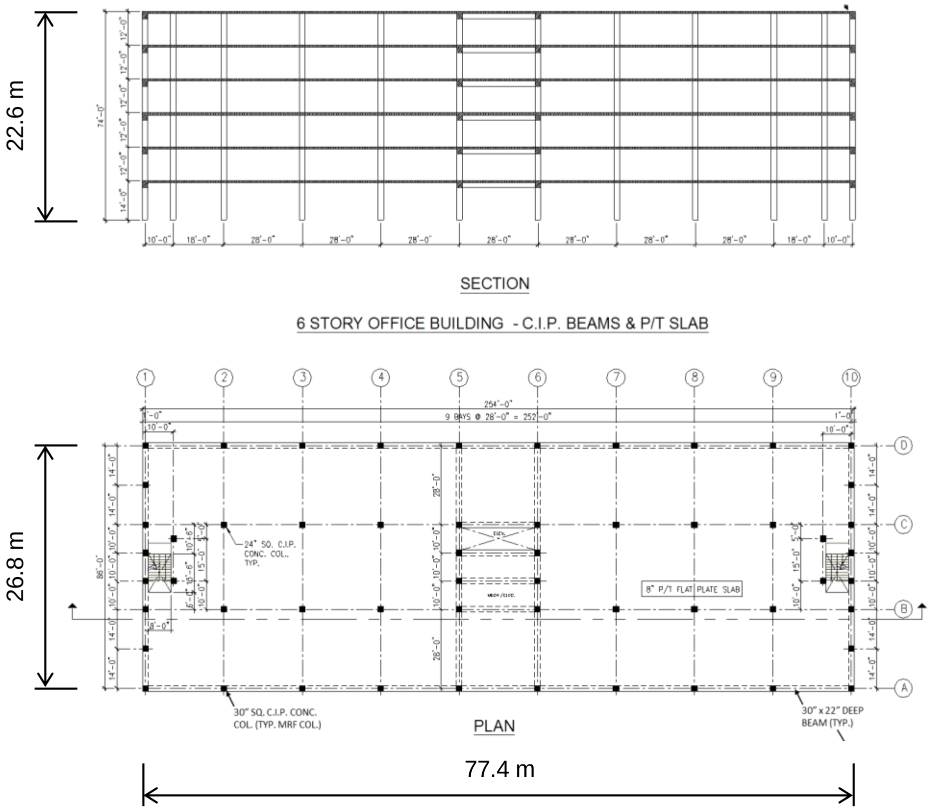

Figure 5. Prototype building (McKamey & Robertson, 2019).

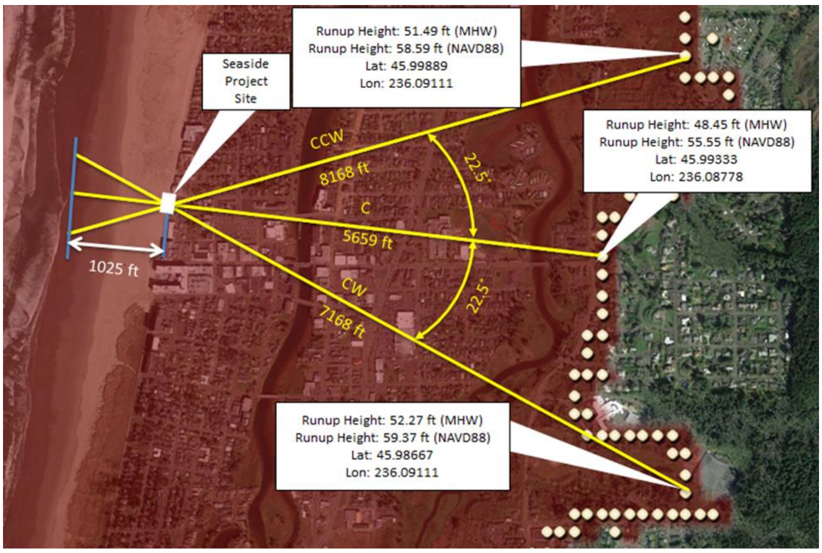

Figure 6. Energy Grade Line Analysis at building site in Seaside (McKamey & Robertson, 2019).

The case study building consists of RC special moment resisting frames (SMRF), a flat plate post-tensioned concrete floor system, and interior gravity load columns, as shown in Figure 3. It was designed for the ASCE 7 wind and seismic loads specified for Monterey, California (Robertson, 2019). The building design is appropriate for Seaside, which has similar seismic hazard to Monterey. Soil classification D for stiff soil is assumed for the building site. The lateral force resisting system consists of four SMRFs in the narrow direction (also the assumed tsunami flow direction) and two moment resisting frames in the wide direction (Figure 5). The size of the columns is uniform along the height of the building, i.e. 71.1x71.1 cm for the SMRFs, and 61x61 cm for the internal gravity load columns, while the size of beams is 76.2 wide by 61 cm deep. The concrete cover is 5 cm. In the SMRF columns, steel reinforcing ratio varies from 1.3% at the ground floor to 1% at the upper stories. Transverse reinforcement in the SMRF columns consists of ties with three 9.5-mm-diameter legs at every 10 cm in the column ends (71 cm long) and every 15 cm in the central section. More details about the seismic design of the building can be found in Yokoyama and Robertson (2014). Complete tsunami design examples for this building and others located at Monterey, Hilo and Waikiki are provided in McKamey & Robertson (2019).

Finite element model

The case-study building is modelled in OpenSees (McKenna et al. 2013) as a two-dimensional model replicating one half of the full structure. Figure 7 illustrates a sketch of the model that includes: one end moment resisting frame (with 8 column), one interior moment resisting frame (with 6 columns), six exterior columns that form part of the transverse exterior moment resisting frames, and six internal gravity columns. All these components are linked by means of master-slave node control so as to simulate a rigid diaphragm at each floor level.

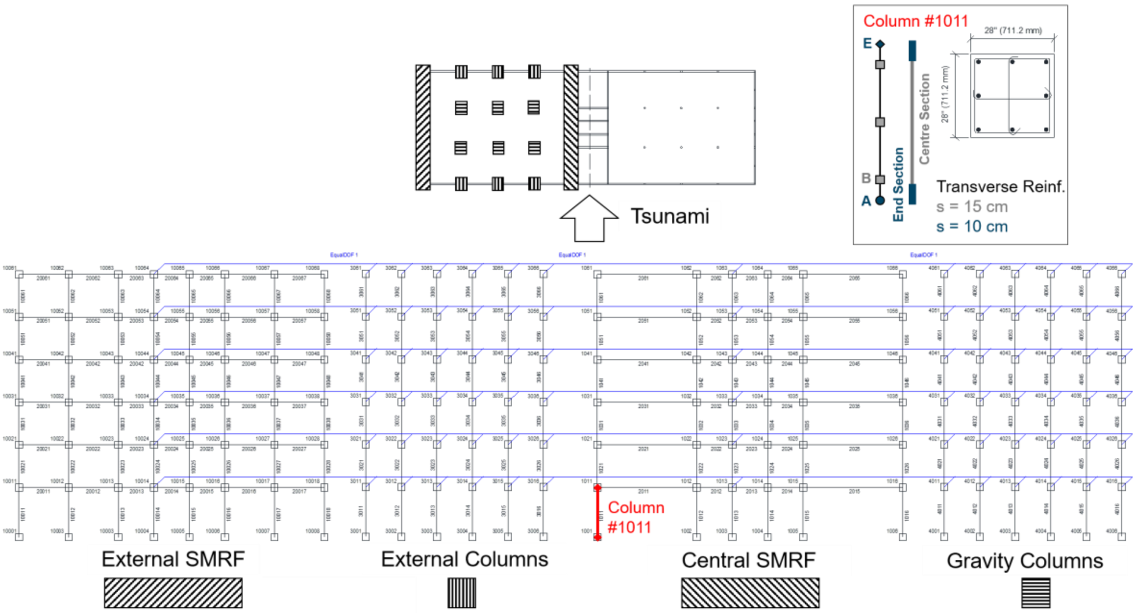

Figure 7: View of the two-dimensional finite element model (half of full prototype building).

Beams and columns are modelled using force-based nonlinear beam-column elements. A distributed plasticity model is adopted, since the inelastic behaviour due to tsunami pressure can form at any point along the column height. A fibre approach is used for the cross-sections with five integration points along each element.

In accordance with ASCE 41-13 Table 10-1, realistic in-situ nominal values are used for the concrete compressive strength (41.4 MPa) and reinforcing steel yield and tensile strengths (517 MPa and 776 MPa). The constitutive materials *Concrete04* (Mander et al., 1988) and *Steel02* (Giuffre-Menegotto-Pinto model) is employed for concrete and steel, respectively, in column and beam cross-sections. Concrete within the reinforcement cage is associated with a confined concrete constitutive law, while the cover concrete outside the reinforcement cage is modelled as unconfined concrete.

In previous studies (Petrone et al., 2017; Alam et al., 2018), it was highlighted that a typical collapse mechanism under tsunami loading is the occurrence of shear failure of columns. This often precipitates global failure if no strengthening measures are adopted. In this study, shear failure occurrence is tracked in all first-storey columns (i.e. those subjected to the highest shear demand), according to the formulation used in ASCE 41-13. It is noted that, both the end and central column sections are checked due to differences in their shear reinforcement (Figure 7). The OpenSees model does not evaluate shear failure, so a separate shear check is performed on all columns post-analysis.

Results

Prescriptive systemic acceptance criterion

ASCE 7-16 provides a simple criterion to evaluate the systemic tsunami capacity of a seismically-designed structure. This assumes that a building designed to resist high seismic loading (i.e. Seismic Design Criteria D, E or F), has sufficient inherent strength to resist the tsunami force *(Chock et al., 2018)*. Effectively, this implies that structural lateral force resisting system does not require additional lateral strength when:

$$F_{\mathrm{T}} < 0.75\Omega_0 E_{\mathrm{h}} \tag{2}$$

where Ω_0 is the system seismic overstrength factor, and E_{h} is the effect of horizontal earthquake forces. From the design of the prototypical building (Ω_0 = 3 for special MRFs, based on ASCE 7 Table 12.2-1), $\Omega_0 E_{\mathrm{h}}$ = 30,123 kN. Given that the applied tsunami force F_{T} = 34,692 kN at LC2 as per Eq. 1 (see Figure 2), the systemic acceptance criterion described in Eq. 2 is not met. The seismic lateral force resisting system would need to be strengthened so as to meet this criterion.

Nonlinear pushover analysis

The lateral capacity of the structure to resist tsunami loads is evaluated using the improved VDPO. To draw a consistent comparison between the actual lateral tsunami capacity with the corresponding seismic one, a seismic pushover analysis is also performed. The seismic pushover is conducted using a lateral load distribution corresponding to the first mode response (fundamental period = 0.8 s; first mode characterised by 83% mass participation factor.

Figure 8 shows the total base shear-top drift curves from the seismic pushover analysis with the one from the VDPO with discretisation method S and C. The actual seismic lateral capacity (16,839 kN) is significantly larger than the design one (10,041 kN). However, it is substantially less than that predicted by the use of an overstrength factor Ω_0 = 3 (30,123 kN). The tsunami pushover curves shows that, for both S and C loading conditions, the systemic tsunami capacity of the building is significantly larger than the overall tsunami at LC2 (F_{T} = 34, 954 kN, shown as a thick dashed line in Figure 8). This assessment contradicts the results of the simplified ASCE 7-16 systemic tsunami capacity acceptance criterion, and would indicate that the structure is safe for use as a refuge without additional strengthening. However, ASCE 7-16 also requires that every structural element be evaluated for component loads. This assessment was done iteratively for each seaward column using loading discretisation C; the worst load combination is presented here (Figure 8 bottom). It can be seen that column shear failure occurs in all seaward columns. As expected, the external SMRF column with the increased component loading is the first column to fail in shear (preceding the shear failure of the other seaward columns). Interestingly, the seaward columns fail in shear in their central sections (i.e., sections B), indicating component failure results in a premature failure of the structure.

If shear failure of the first column is assumed as the structural failure criterion, the resulting tsunami capacity of the building is almost a third of the design tsunami load. This analysis results in the same conclusions as the simplified ASCE 7-16 systemic tsunami capacity acceptance criterion, i.e. that the structure is not safe for use as a refuge without additional strengthening. However, the use of the VDPO provides information of what needs to be strengthened in order to improve the tsunami performance of the structure, i.e. the shear strength of the ground floor seaward columns, in this example case. For instance, by increasing the shear reinforcement in the central sections (spacing from 15 cm to 10 cm; see Figure 7) of all seaward columns, shear failure would only occur at Section A, i.e. the tsunami capacity of the structure would double.

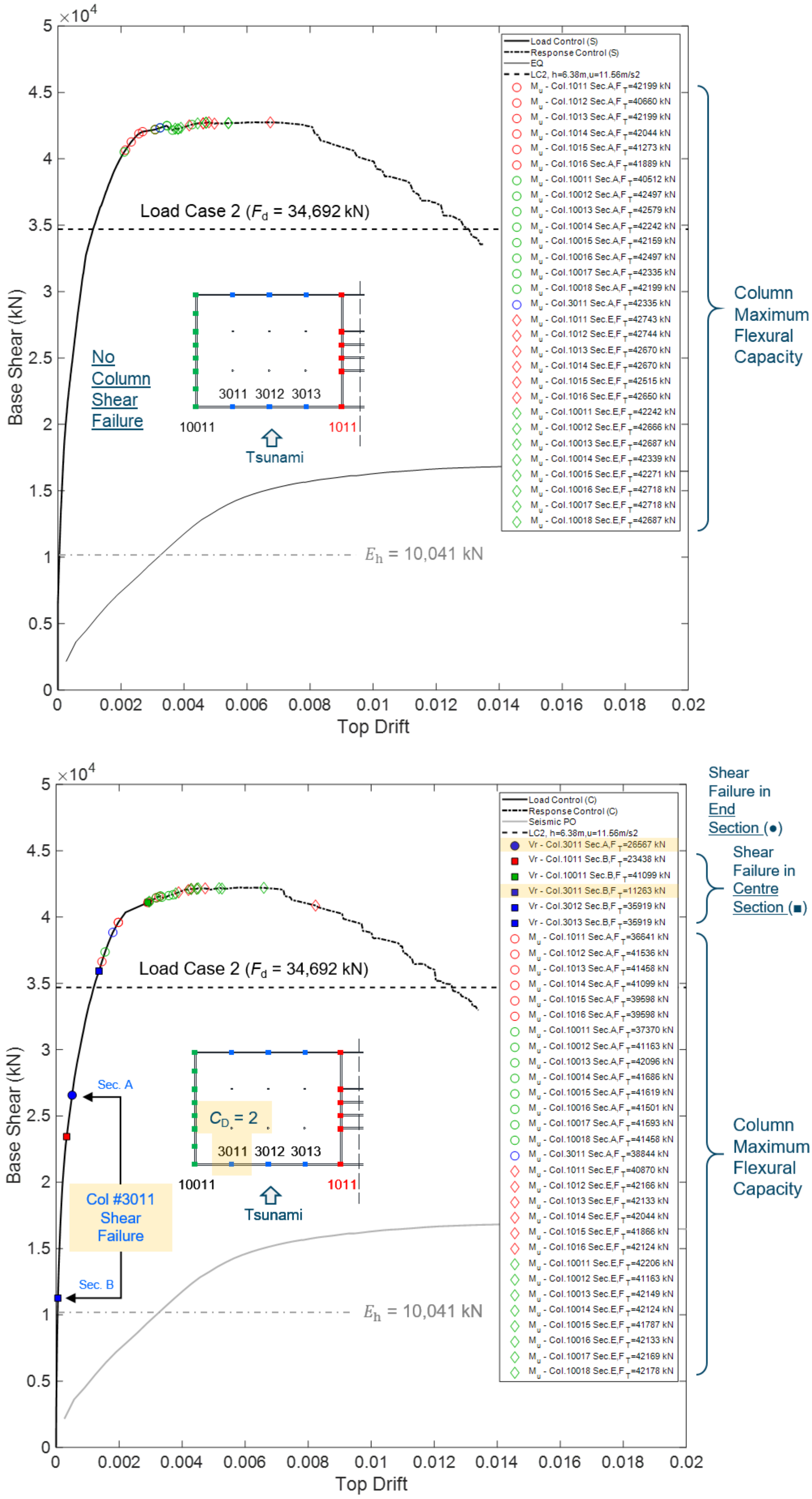

Figure 8: Base-shear-top drift curves from seismic PO and tsunami PO with load discretisation method S (top) and C (bottom), with sequence of maximum flexural capacity and shear failure attainment (for ground floor columns)

Conclusions

New tsunami design provisions in ASCE 7-16 Chapter 6 offer a practical methodology for the design of buildings to tsunami. While the use of performance-based analysis tools is permitted, no specific guidance is provided. This study presents an improved variable depth pushover analysis approach (VDPO) for the assessment of the non-linear capacity of structures subjected to tsunami. The analytical results are compared to the simplified ASCE 7-16 systemic tsunami capacity acceptance criterion for a case study RC frame located in a high tsunami hazard area. The response of the structure was investigated using VDPO, applying two different tsunami load discretisation methods. For both load discretisation cases, the tsunami systemic capacity of the structure was seen to be sufficient to resist the ASCE 7-16 prescribed tsunami loads. However, when component loading was considered, the seaward ground storey columns were observed to fail in shear, precipitating structural failure. Overall, the VDPO analysis, considering component behaviour, provided the same result as the ASCE 7-16 simplified systemic acceptance criteria, i.e. that the structure was unsafe for use as a refuge, and that it would require significant strengthening. By applying the component loading procedure, the user can identify the structural elements that may need to be strengthened, to meet the design acceptance criteria (e.g. ground floor columns that need more shear resistance). This approach is going to be further tested to check the cost savings that can be achieved through its implementation. In addition, the effect of the preceding earthquake will be addressed in a separate stage of this research work.

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