
Accounting for higher mode effects when designing the primary structure and floor diaphragms of a tall building

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ABSTRACT

The design of a 34-storey building in Auckland currently being undertaken by Holmes has highlighted the importance of considering higher mode effects, particularly when designing the floor diaphragms. There is a lack of guidance on the design for higher mode effects in the NZ design standards (e.g. NZS1170.5:2004) thus making it harder to establish realistic loading for the design of some taller structures, and to determine a credible compliance pathway to meet the intent of the Building Code.

Using this project as an example, this paper summarises:

- How higher mode effects were accounted for in the design of the structure, noting that the base shear from the MRSA is larger than an ESA due to higher mode effects, which is a case not intended by the scaling provisions of NZ1170.5:2004.
- How the MRSA analysis results were used to modify pESA loading profile for diaphragm design procedure set out in NZS1170.5:2004, by allowing for the higher inertia loads occurring over the middle half of the building height due to higher mode effects.
- Scaling up of the pESA loading profile to match the MRSA storey shears and account for increased transfer effects in the diaphragms, particularly at the upper and lower levels.
- Ensuring that the design incorporated an adequate level of robustness as intended by NZS1170.5:2004, without adding unnecessary conservatism and thus cost to the project. The paper covers how a robust design can be achieved with relatively standard analysis tools/methods, without the need for additional complicated analysis procedures which can be time-intensive and hard to verify.

The paper is intended to be helpful as a design example for other engineers working on tall buildings/structures where higher modes play a significant role.

1 INTRODUCTION

NZS 1170.5:2004 accounts for higher mode effects through the requirement of modal response spectrum analyses (MRSA) for buildings suitably irregular, tall, and flexible (Standards New Zealand 2004). MRSA analyses account for the mass participation of each mode up to 90% of the total mass of the structure while an equivalent static analysis (ESA) only accounts for and distributes storey forces to emulate the first mode of response of the building in each direction, with some load lumped at the top to simplistically allow for higher mode effects. Higher modes inherently have increased spectral accelerations per NZS 1170.5:2004 and can therefore increase the base shear on the structure where these modes have a large mass participation and form a large component of the response. NZS1170.5:2004 requires the designer to scale design actions for a building classified as irregular under the standard by a scale factor, k , equal to the base shear found from ESA method divided by the base shear found from MRSA method ($V_{b,MRSA} / V_{b,ESA}$). For typical building configurations the ESA base shear generally exceeds the MRSA base shear where higher mode effects don't have a large mass participation. Where MRSA base shear exceeds ESA base shear (the case for this building), no scaling is required and $k = 1.0$.



Figure 1. 34 storey building under design in Auckland (extracted from ETABS structural analysis programme)

In cases where MRSA base shear exceeds ESA base shear the design of the diaphragms is less clear. Diaphragms designed following NZS 1170.5:2004 typically use the pseudo-equivalent static analysis (pESA) method which requires the designer to apply a modified ESA loading envelope to the building, amplified by the building overstrength factor (ϕ_{ob}) to achieve suitable robustness (Standards New Zealand 2004). The maximum value of lateral force applied to the diaphragms can be taken as 1.5x the elastic ESA loading envelope ($\mu = 1.0$, $S_p = 1.0$) (Standards New Zealand 2004). As the design of diaphragms necessitates the difference in shear forces at lateral load resisting elements above and below the diaphragm to be extracted from the analysis, the actions in the lateral elements are required to be in equilibrium. MRSA design actions on elements are determined through a square root sum of squares approach of the participating modes, and

therefore the design actions are not in equilibrium and MRSA outputs are not appropriate for conventional diaphragm design. Where MRSA base shear exceeds ESA base shear, applying the pESA loading profile should be adequately scaled to account for the higher MRSA base shear. In addition to this, the pESA loading profile is only considered valid for buildings up to 9 storeys in height and is intended for use with concrete frame buildings only (Standards New Zealand 2004). These factors result in an unclear compliance pathway for diaphragms in taller buildings.

Table 1: First 16 building modes and mass participation factors (extracted from ETABS structural analysis programme)

Mode	Period (s)	UX	UY	SumUX	SumUY
1	5.351	0.6306	0.0034	0.6306	0.0034
2	3.694	0.003	0.4828	0.6336	0.4863
3	2.732	0.0021	0.0907	0.6357	0.5769
4	1.086	0.1515	0.0008	0.7871	0.5778
5	0.81	0.0002	0.0513	0.7873	0.6291
6	0.599	0.0016	0.1314	0.789	0.7606
7	0.47	0.0465	0.0007	0.8354	0.7613
8	0.391	1.09E-06	0.0001	0.8354	0.7614
9	0.389	0.0005	3.81E-06	0.836	0.7614
10	0.352	0.0004	0.0109	0.8363	0.7723
11	0.277	0.0312	0.0003	0.8676	0.7726
12	0.244	6.84E-06	0.06	0.8676	0.8326
13	0.232	0.0019	0.0001	0.8695	0.8326
14	0.215	0.0016	2.08E-05	0.8711	0.8327
15	0.207	0.0003	0.0053	0.8714	0.838
16	0.191	0.0201	2.96E-06	0.8915	0.838

An image of the 34 storey Auckland building analysis model under design that serves as a case study for this paper is shown in Figure 1. Table 1 shows the modal participation outputs from the analysis and the contribution of modes with higher spectral accelerations (periods of approximately 1.0 s or less). The fundamental periods in the X direction and Y direction are 5.3 s and 3.7 s respectively. The MRSA base-shear is higher than the ESA base-shear due to the higher modes dominating the response of the building (as indicated by the highlighted modes in Table 1, with the spectral accelerations associated with these modes being much higher than that of the primary modes, hence them dominating the response). It is important to note that at the writing of this paper the analysis and design of the building is ongoing and the analysis results shown are preliminary.

2 MODIFICATIONS TO PSEUDO EQUIVALENT STATIC LOADING PROFILE FOR DIAPHRAGM DESIGN

2.1 Modifications for diaphragm transfer actions

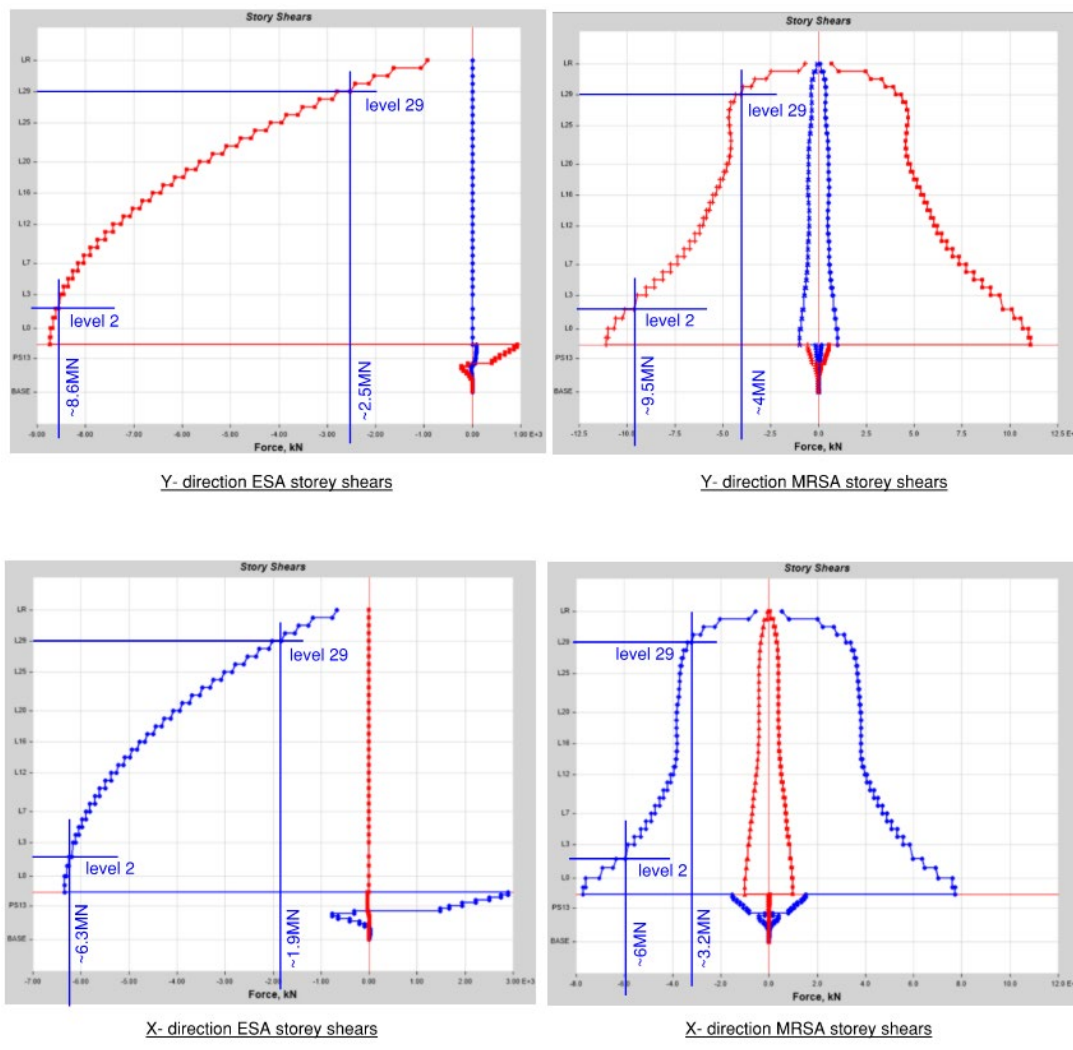


Figure 2. Summary of scale factors applied to pESA forces

The case study building is designed as a nominally ductile structure. The building overstrength for the diaphragm design, $\phi_{ob} \times V_{b,design}$, is capped at 1.5x elastic load in accordance with NZS 1170.5:2004 (Standards New Zealand 2004). The use of this capped loading may be too conservative for other buildings in other regions of New Zealand and/or buildings designed for a higher ductility. The pESA force envelope is applied to the model to determine diaphragm transfer actions, generally comprising of the 1.5x ESA force distribution ($\mu = 1.0$, $S_p = 1.0$), capped in accordance with NZS 1170.5:2004[but modified with an additional amplification factor applied on a diaphragm level-by-level basis where the MRSA story shear is greater than the ESA storey shear as described below. This results in a diaphragm transfer force distribution which was increased for the upper and lower portions of the building to maintain the appropriate margin between diaphragm transfer forces (based on 1.5x ESA actions with $\mu = 1.0$, $S_p = 1.0$) and the vertical lateral force element design actions (based on MRSA actions).

Across the typical levels (levels 4 to 22), the ESA load-case storey shear exceeds the MRSA storey shear as shown in Figure 2. Therefore, the standard 1.5x ESA ($\mu = 1.0$, $S_p = 1.0$) force envelope is considered appropriate for the determination of the diaphragm transfer effects at these levels.

The majority of diaphragm transfer occurs in this building at levels 2 and 3 where there is a significant change in the vertical and lateral loading resisting elements (wall length at boundaries increases significantly - see Figure 1). To maintain the robustness intended by the pESA method (diaphragms able to transfer overstrength actions), the 1.5x ESA ($\mu = 1.0$, $S_p = 1.0$) force distribution at these primary diaphragms is amplified by a further 1.1x factor in the X-direction and the Y-direction.

The 1.1x factor is calculated in each principle direction as the ratio of the MRSA / ESA storey forces illustrated in Figure 2 (e.g. $V_{L2,MRSA,Y} = 9.5\text{MN}$ and $V_{L2,ESA,Y} = 8.6\text{MN}$; $V_{L2,MRSA,X} = 6.3\text{MN}$ and $V_{L2,ESA,X} = 6.0\text{MN}$).

The 1.5x ESA ($\mu = 1.0$, $S_p = 1.0$) force distribution is amplified by a further 1.25x factor below level 2 (based on the difference in MRSA / ESA storey forces at that level). Similarly, a further amplification factor of 1.6x and 1.7x is applied to the Y-direction and X-direction 1.5x ESA ($\mu = 1.0$, $S_p = 1.0$) forces respectively (at the upper levels only) to account for the higher mode effects, reflecting level 29 where the MRSA / ESA scaling factor is the largest (e.g. $V_{L29,MRSA,Y} = 4.0\text{MN}$ and $V_{L29,ESA,Y} = 2.5\text{MN}$; $V_{L29,MRSA,X} = 3.2\text{MN}$ and $V_{L29,ESA,X} = 1.9\text{MN}$).

As noted above, the additional amplification factor is determined on a level-by-level basis (based on the MRSA vs. ESA storey shear at that level). This is considered appropriate as it is relevant to the diaphragm transfer forces at the level in question. This is done instead of determining one additional amplification factor from the MRSA vs. ESA base shear ($V_{b,MRSA} / V_{b,ESA}$) and applying that factor at all levels. Applying just one amplification factor over the height of the building would have resulted in unnecessary conservatism being added to the transfer actions at some levels (e.g. at levels 2-3), and unconservative actions being applied at the upper levels (as the amplification at these levels was determined to be much higher – likely due to higher mode effects).

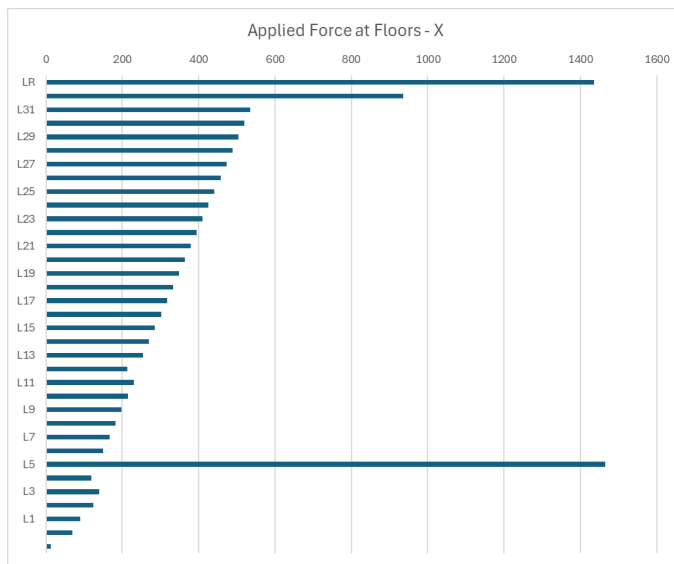
This case study demonstrates a novel approach for accounting for higher mode floor accelerations. As the development of this application to date has been based on a single case study building, it may be recommended that NLTHA is used to validate the approach if it were to be applied more widely.

2.2 Modifications for diaphragm inertia actions

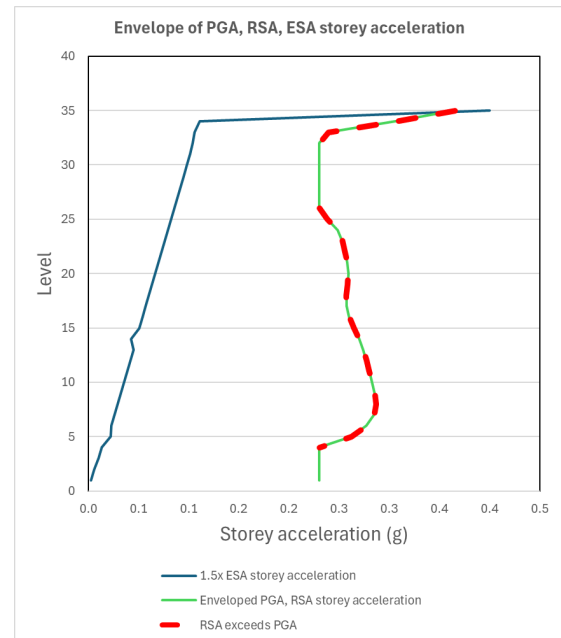
The pESA loading profile requires the designer to apply the maximum of either a storey force corresponding to peak ground acceleration (PGA) applied to the seismic weight of the storey, or ESA actions corresponding to the overstrength building shear (capped at 1.5x ESA with $\mu = 1.0$, $S_p = 1.0$ for this project) at each level (Standards New Zealand 2004). Peak diaphragm actions in a building do not occur simultaneously and therefore PGA actions need only be applied at one level at a time to capture the most adverse inertia forces (Standards New Zealand 2004). Figure 3a shows the distribution of diaphragm forces applied to analyse a typical level of the case study building (level 5).

As the building is dominated by higher mode effects, and given that the pESA method is not a compliant solution following NZS1170.5:2004 for buildings taller than 9 storeys, it was necessary for further investigation to be carried out to determine peak diaphragm inertia forces. To achieve this, the diaphragm accelerations are extracted from the ETABS model and compared with PGA and ESA accelerations (see Figure 3b). It can be seen from Figure 3b that PGA and/or MRSA accelerations govern significantly over 1.5x ESA ($\mu = 1.0$, $S_p = 1.0$) actions for all general levels. The most adverse case for diaphragm inertia forces (green line in Figure 3b) is applied on a level-by-level basis, along with the modified 1.5x ESA force distribution over the height of the building to capture transfer effects (as described in Section 2.1).

This approach is considered to provide a suitable level of accuracy to the diaphragm design, whilst being a significantly more cost-effective and less analysis-heavy approach at estimating project specific diaphragm inertia forces than (for example) in undertaking a time-history analysis of the building including diaphragms.



a) Distribution of diaphragm actions for the design of the example level 5 (note the larger inertia load applied at level 5 to match the modified pESA envelope)



b) Modified envelope of pESA and MRSA accelerations up the height of the building

Figure 3. Modified pESA acceleration distribution

3 CONCLUSIONS

The pESA method provides a simple and robust method for the analysis of diaphragm actions in multi-storey buildings, however its limitations on use can result in ambiguity on the most appropriate analysis approach for diaphragms that do not fall within the scope of the pESA method (e.g. where higher mode effects are significant). Modifications to the pESA loading profile have been undertaken for the case study building which the designers believe result in a suitably robust and accurate method to account for the peak diaphragm inertia and transfer forces, whilst incorporating the intent of the pESA method without requiring too much additional analysis effort.

Additional amplification of the ESA loading envelope used to determine the transfer actions (1.5x ESA with $\mu = 1.0$, $S_p = 1.0$ for this project) is proposed to account for cases where the MRSA storey shears are larger than the ESA storey shears. This amplification is proposed to be calculated on a diaphragm level-by-level case rather than determining a common additional amplification factor from the building base shear ($V_{b,MRSA} / V_{b,ESA}$), thus preventing unnecessary and potentially costly over-design of the key transfer diaphragms or conversely under-design of diaphragm elements subject to larger actions due to higher mode effects.

4 ACKNOWLEDGEMENTS

This approach to account for higher mode effects in the analysis of tall buildings was developed in conjunction with Robert Bird Group, the peer reviewer on the project.

REFERENCES

Standards New Zealand (2004). "NZS1170.5: *Structural Design Actions. Part 5: Earthquake Actions - New Zealand incl. Amendments 1-3*". Standards New Zealand, Wellington, 76pp.
<https://www.standards.govt.nz/sponsored-standards/building-standards/NZS1170-5>