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Industry CPD

Modelling buildings for seismic analysis

This CPD module, sponsored by SCIA, introduces best practice guidelines for performing seismic analysis using the Modal Response Spectrum Method in finite element software. These principles ought to be well understood when applied to 3D models.

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1 hour of verifiable CPD

Increasingly challenging structures are designed nowadays, for which traditional, simple methods are no longer applicable. Finite element software products have become standard tools for structural engineers, including the ever-increasing use of 3D modelling. These tools are usually well mastered for static analysis. However, there are often grey areas when it comes to seismic analysis and design. Although it might sometimes look like it, finite element software – as any software – is not a magical tool that can solve everything in just a few clicks.

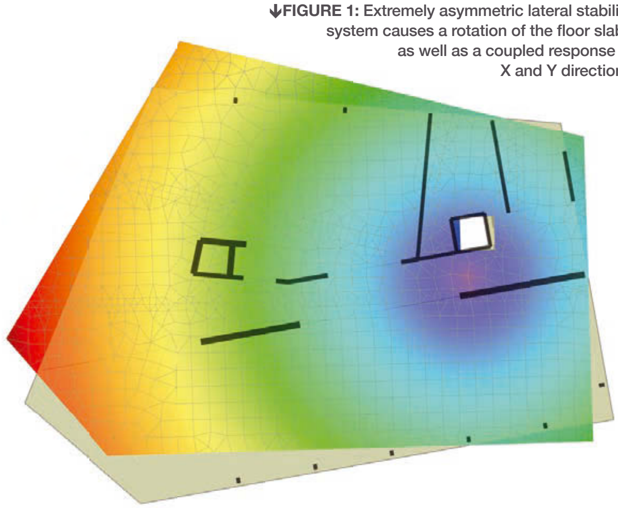
Why use a 3D model?

For most projects, a 3D model is already produced during the static design phase. Re-using and adjusting it for seismic design is a natural solution. Aside from that, complex building geometries and architectural demands often result in the structure being classed as irregular in plan, which excludes using simplified planar models **(Figure 1)**.

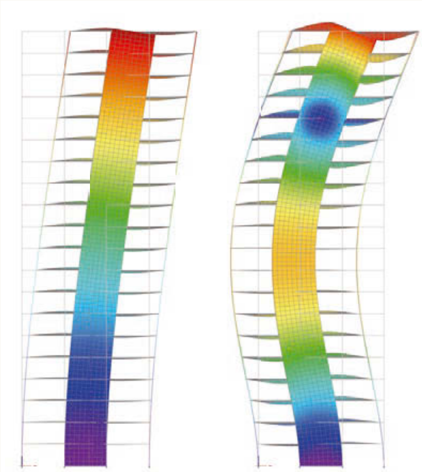
MRSM vs ELF

The Equivalent Lateral Forces (ELF) method is very popular, as it benefits from the vast experience of static analysis and design that all structural engineers possess. However, it applies only to buildings that fulfil conditions of regularity in elevation and overall horizontal stiffness. Frequently buildings do not satisfy the conditions of regularity in elevation. Additionally, buildings with a high value of fundamental period are likely to attract predominant participation of non-fundamental modes **(Figure 2)**. This contradicts the basic assumption of the ELF method: the fundamental mode governs the behaviour of the structure.

In such cases, the ELF method is not applicable, and the **Modal Response Spectrum Method** (MRSM) should be used instead.



↓FIGURE 1: Extremely asymmetric lateral stability system causes a rotation of the floor slabs as well as a coupled response in X and Y directions



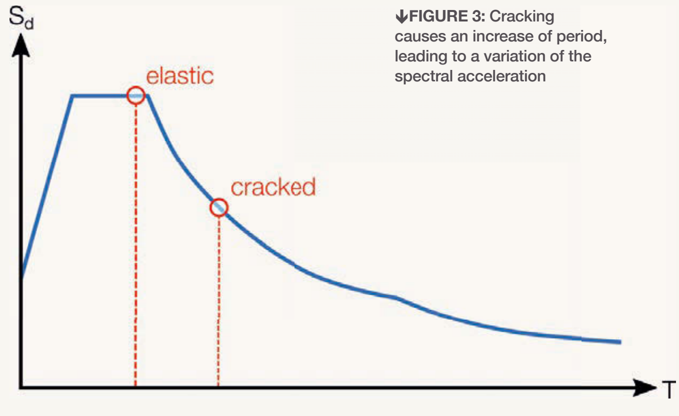
↑FIGURE 2: The 2nd order mode (right-hand side) may have a higher contribution than the fundamental mode (left-hand side) for long-period structures (typically $T_1 > 2$s)

Why use a separate model?

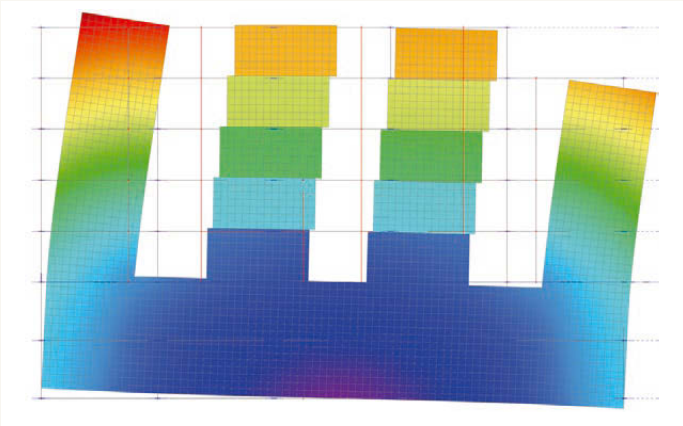
It is tempting to simply add seismic loading to a full 3D model that has been prepared for static analysis. However, there are many more aspects that need adjusting before applying MRSM. Unless the used finite element software can handle multi-model analysis, it is recommended to create a copy, adapt it, and keep it separate from the static model.

Diaphragms

When possible, rigid diaphragms (i.e. in-plane stiffness only) can be used for the floor slabs. It removes unwanted frame effects from the model (absence of bending stiffness) and, at the



↓**FIGURE 3:** Cracking causes an increase of period, leading to a variation of the spectral acceleration



↑**FIGURE 5:** Reinforced concrete shear walls (leftmost and rightmost) are continuous; secondary masonry walls (centre two) are partly disconnected using hinges, allowing the slabs to slide on the top of them freely

←**FIGURE 4:** Shear wall with hinged connections; fixed in-plane DoF (left) and free out-of-plane rotations

same time, considerably reduces the number of degrees of freedom and computation time.

Shear-resisting systems for overall lateral stability

For concrete or masonry shear walls, cracking must be considered. Cracks directly affect the stiffness of the structure, its natural frequencies and mode shapes. Ultimately, this influences the applied accelerations and all other results **(Figure 3)**.

Planar lateral stability systems are usually designed to work in their own plane. Therefore, in the model, they should only be allowed to work in the corresponding direction. Typically, out-of-plane disturbances can be avoided by freeing relevant degrees of freedom **(Figure 4)**. Allowing out-of-plane internal forces – e.g. out-of-plane bending in a shear wall – might reduce the internal forces in the perpendicular bracing elements, leading to an unsafe design of the latter.

On the other hand, when the actual detailing of a bracing element induces out-of-plane effects, this **must be considered** in its analysis and design as well, and vice versa.

Secondary supporting members

How secondary supporting members are modelled must be carefully considered. Such members are typically walls or columns supporting gravity loads. They are essential to guarantee the integrity of the structure, but they do not contribute to the overall lateral stability.

Secondary supporting members may be ignored in the seismic analysis model, if their contribution to the overall lateral stiffness is insignificant. If their contribution to the stiffness is significant, they might attract internal forces under seismic loading, which must be considered in their design. Failing to do so can lead to their collapse during an earthquake, potentially leading to a progressive collapse of the entire structure under gravity loading. Note that their stiffness may be removed from the analysis model, but not their mass.

Alternatively, secondary supporting members may remain in the model with an appropriate connection to the rest of the model **(Figure 5)**, provided that corresponding detailing is put in place and communicated at construction.

Boundary conditions

For buildings, dynamic soil-structure interaction is usually not a topic of concern and the seismic action may be considered simply as input data. Said input is the motion of the ground below the foundation. In common analysis methods (ELF, MRSM, pushover), the foundation of the building is referential **(Figure 6)** and response spectra are defined according to that assumption. Therefore, in the analysis model, the foundation of the building is fixed.

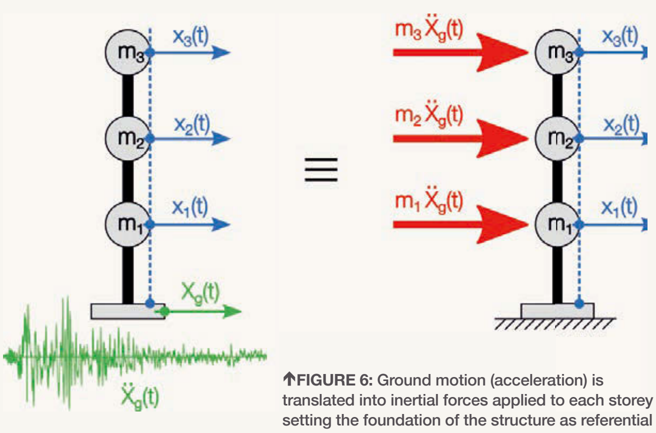
The flexibility of the foundation soil may be taken into account in special cases, provided that the response spectrum is adjusted accordingly.

Some rotation of the foundation may be allowed under horizontal seismic action (rocking), which most of the time corresponds to applying flexible boundary conditions in the vertical direction.

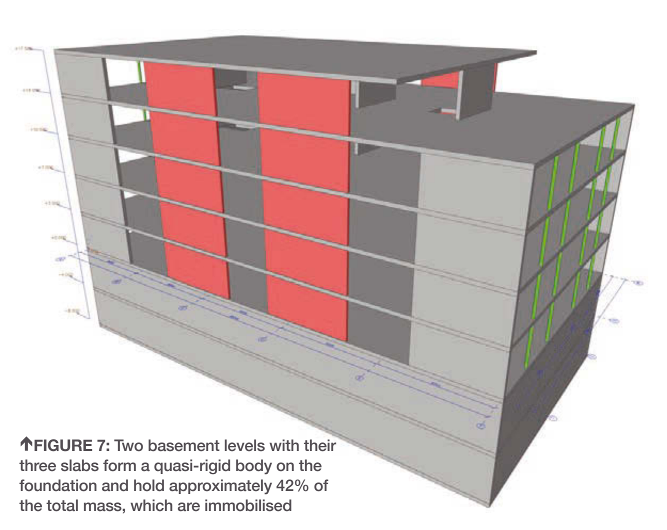
Structural and accidental eccentricity in MRSM

The structural eccentricity of a building is due to the irregularity in plan of the structure. It is the distance between the centre of mass and the centre of stiffness, which causes an overall torsion effect. In 3D models, this effect is implicitly taken into account.

Accidental eccentricity is due to unpredictable variations of the mass distribution, usually related to the distribution of live loads in reality. The preferred computation method for accidental eccentricity effects is similar to ELF analysis and consists of defining a set of static moments about the global vertical axis of each storey and superposing their effect onto the MRSM results.



↑**FIGURE 6:** Ground motion (acceleration) is translated into inertial forces applied to each storey by setting the foundation of the structure as referential



↑**FIGURE 7:** Two basement levels with their three slabs form a quasi-rigid body on the foundation and hold approximately 42% of the total mass, which are immobilised

Modal superposition

All seismic design standards somehow state in their description of the MRSM, that *the response of all modes of vibration contributing significantly to the global response shall be taken into account*.

That key principle usually translates into the condition, that the cumulated effective modal mass of all considered modes amounts to at least 90% of the total mass of the structure. Alternative conditions are often proposed.

Often it is difficult to achieve 90% of effective modal mass when using a 3D model. Simply increasing the number of computed modes is pointless. The issue is mainly due to two causes: immobilised masses and local modes.

Immobilised masses are masses that are located near supports. Consequently, such masses cannot vibrate, or the corresponding frequency is so high, that it is out of the range of seismic excitation. Often these masses are irrelevant for the design of lateral stability systems and therefore can be ignored **(Figure 7)**.

If, for some reason, immobilised masses cannot be ignored – e.g. design of the foundations – the residual pseudo-mode technique may be used. This technique assumes that the missing effective modal mass is associated with a rigid mode behaviour. The ground acceleration may be applied to that missing mass as a static load. The static response can then be inserted into the modal superposition as a *pseudo-mode*.

Local modes are local vibration modes that set tiny portions of the structure in motion and are irrelevant for the overall shear-system behaviour. They can "pollute" the analysis results and increase computation time because many unnecessary modes will be calculated before the relevant modes, for seismic design, are determined. Truss structures are examples of this behaviour. The easiest way to avoid local modes is to remove the irrelevant degrees of freedom from the mass matrix. Two practical ways of doing this are: coarsening the finite element mesh of problematic members, or redistributing their mass to stiffer adjacent elements.

Having obtained the required modes, modal superposition may be applied. In 3D models, especially complex ones, the preferred method is the Complete Quadratic Combination (CQC), as it considers mode interferences. SRSS (Square Root of Sum of Squares) superposition is only valid if modes are independent.

Signed results

Seismic accelerograms describe specific seismic events and using them requires multiple full time-history analyses. Instead, a standardised response spectrum represents an envelope of probable seismic events at a given location. The MRSM aims to obtain envelope values of the effects of the seismic action, at a much lower computation cost.

As a result, seismic modal superposition (SRSS or CQC) only returns an approximation of an **envelope** of the time-history response **(Figure 8)**, without the actual time trace.

The values obtained from modal superposition are unsigned and do not provide enough information about concomitant forces. This means, for instance, that it is possible to know the min and max axial force and bending moment that occurs in a member. However, **it is not possible to know the value (nor sign) of the axial force that occurs at the same location as maximum (or minimum) bending moment**, and vice versa. This is a problem for the design and subsequent checks.

Signing the obtained results is a commonly used solution and is based on the following assumptions:

- →| All variables peak simultaneously (min or max)
- →| The relative sign of all variables is governed by a predominant mode shape

The obtained signed envelope **(Figure 9)** may then be used for the structural design or check, applying it alternatively with a +1 or -1 coefficient accounts for force reversal.

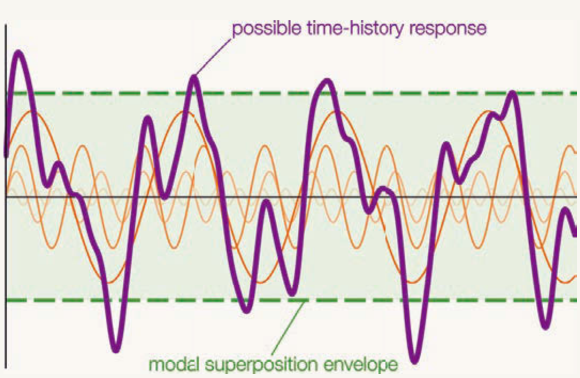
Conclusion

The Modal Response Spectrum Method is a convenient and powerful tool that can be used for the seismic analysis of most structures. However, using it efficiently and safely requires knowing its principles and limitations. When using a finite element software for seismic analysis, having a good understanding of the underlying assumptions is of the utmost importance.

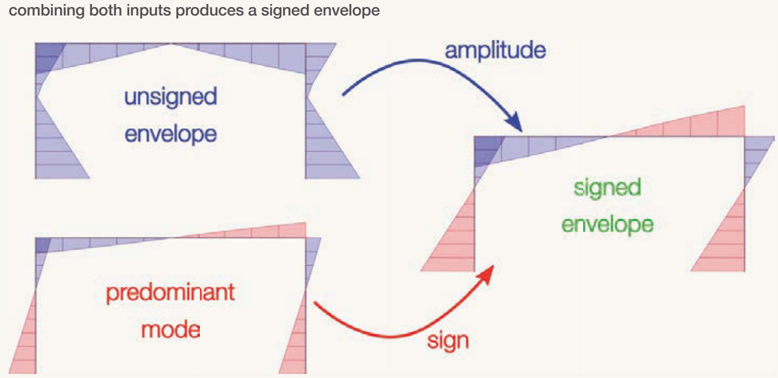
Final note

Practical rules corresponding to the above recommendations are provided in most seismic design standards. They can be found in Sections 4.1 to 4.3 in Eurocode EN 1998-1.

↓**FIGURE 8:** Possible time-history response (based on arbitrary phase values) and corresponding modal superposition envelope (phase-independent)



↓**FIGURE 9:** Modal superposition provides unsigned peak values; signs are obtained from the predominant mode, selected based on the highest effective modal mass; combining both inputs produces a signed envelope



Questions

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1. What are the reasons for using a 3D model for seismic analysis? (tick *all* relevant answers)
- ☐ The layout of the lateral stability system is asymmetrical
- ☐ The building is irregular in plan
- ☐ The building is irregular in elevation
- ☐ Planar models cannot be handled by 3D FEM software

2. What adjustments should be made when adapting a static analysis model for MRSM analysis? (tick *all* relevant answers)
- ☐ Remove all hinges
- ☐ Carefully consider how secondary supporting members are modelled and connected to the rest of the structure
- ☐ Adjust the stiffness of steel members
- ☐ Adjust boundary conditions to match MRSM assumptions

3. What are the benefits of using rigid diaphragms instead of finite element plates? (tick *all* relevant answers)
- ☐ Reduction of computation time
- ☐ Output of results for the design of floors
- ☐ Removal of unwanted frame effects
- ☐ Elimination of local modes in slabs

4. Why should the stiffness of concrete and masonry shear walls be reduced for seismic analysis? (*one* answer)
- ☐ Because cracking affects the resistance of shear walls
- ☐ Because cracking affects the natural frequencies of the system, hence directly impacts accelerations
- ☐ Because cracking modifies the behaviour factor and consequently the response spectrum
- ☐ Modification is not necessary

5. Why should out-of-plane effects be avoided in a planar lateral stability system when possible? (*one* answer)
- ☐ To avoid reducing the effects of actions in other bracing elements acting in the perpendicular direction
- ☐ To prevent minor out-of-plane disturbances in the bracing elements
- ☐ To avoid local modes in the bracing elements
- ☐ To simplify the detailing of connections

6. When can secondary supporting members (walls and columns) be ignored for seismic analysis? (*one* answer)
- ☐ When they are not rigidly connected to slabs and do not transmit gravity loads
- ☐ When their mass can be neglected
- ☐ When their cumulated horizontal stiffness does not significantly contribute to the overall horizontal stiffness
- ☐ When they are not vertical

7. Under what conditions should the MRSM be used instead of ELF? (tick *all* relevant answers)
- ☐ The building is irregular in plan
- ☐ The building is irregular in elevation
- ☐ The building is irregular in torsion
- ☐ The fundamental mode is not predominant

8. How can the structural eccentricity be considered in a 3D model? (*one* answer)
- ☐ By applying moments about the global vertical axis corresponding to the eccentricity between the mass centre and the stiffness centre
- ☐ By adding eccentric masses to the model
- ☐ By applying coefficients to results in bracing elements
- ☐ It is considered automatically in 3D models

9. Which of the below is the most likely to significantly reduce the effective modal mass? (*one* answer)
- ☐ A swimming pool on the roof
- ☐ A foundation slab on stiff subsoil
- ☐ An asymmetrical lateral stability system layout
- ☐ A very flexible lateral stability system, resulting in a non-fundamental predominant mode