EARTHQUAKE DYNAMIC ANALYSIS OF A HOSPITAL BUILDING

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ABSTRACT

This paper deals with the construction of the new Acute Care Hospital which forms part of the redevelopment of the Royal North Shore Hospital complex in Sydney. The hospital as a building essential to post-disaster recovery function has the highest importance level for a structure in accordance with AS1170.4:2007. This means that the structure requires dynamic analysis to be performed as the building is more than 12 m in height.

The Acute Care Hospital is 9 storeys high with allowance for 2 additional storeys. It is characterised with irregularities on the floor plate size and layout. The earthquake resistance elements of the building are the shear walls in the form of multiple lift and stair cores.

Using Finite Element Modelling (FEM) software namely Strand7, a three-dimensional computer model was developed and dynamic analysis was carried out using response spectrum method. Dynamic analysis output highlighted the different lateral load distribution among the cores when compared to static analysis and gives an indication of the true principal orthogonal directions of the building.

1 INTRODUCTION

This paper deals with the construction of the new Acute Care Hospital which forms part of the redevelopment of the Royal North Shore Hospital complex in Sydney. The hospital as a building essential to post-disaster recovery function has the highest importance level for a structure in accordance with AS1170.4:2007. This means that the structure requires dynamic analysis to be performed as the building is more than 12 m high.

This paper sets out the principles of using FEM software to assist in carrying out seismic dynamic analysis.

2 EARTHQUAKE DESIGN REQUIREMENTS FOR BUILDING STRUCTURE

2.1 DESIGN ISSUES

The main issues in designing building structure to resist earthquake load are as follows.

1. Seismic-force-resisting system. Structure must have a seismic-force-resisting system with a clearly defined load path or paths, which can transfer the earthquake load to the foundations.
2. Unity of the structure. All parts of structure need to be tied together in a way such that forces generated during earthquakes from all parts of structure are carried to the foundations.
3. Expected deformation under different intensities of earthquake load. Under the effect of minor earthquakes, the main members that are designed to carry earthquake loads should not be damaged; however other non lateral resistant parts of the building may sustain repairable damage. Under the effect of strong earthquakes, the main members may suffer severe or even irreparable damage, but buildings should not collapse.
4. Special requirement for crucial structural elements. All walls must be anchored to the roof, restrained at all floors and designed for both in-plane and out-of-plane forces. In-plane deflection of diaphragm element should not exceed the permissible deflection of the attached elements.

Additional requirements are applicable for important buildings such as a hospital, which play a critical role in post-earthquake activities. After earthquake, the structure must sustain very little damage and must remain functional immediately. AS1170.4-2007 states that 'a special study shall be carried out for importance level 4 structures to ensure they remain serviceable for immediate use following the design event for importance level 2 structures.'

2.2 DESIGN CRITERIA

The following are the general criteria for the ultimate limit state design.

$$R_d \geq E_d \tag{1}$$

where R_d= design capacity = ϕR, E_d = design action effects, ϕ = capacity reduction factor

Design capacity of the structure corresponds to the elements of the structure that carry the design actions. For the earthquake case, AS1170.0:2002 sets out the following design load case combination.

$$E_d = G + \psi_c Q + E_u \tag{2}$$

Where G= permanent action (self-weight or 'dead' load), E_u= ultimate earthquake action, Q= imposed action (due to occupancy and use, 'live' load), ψ_c = combination factor for imposed action

Besides earthquake actions, the design load of a structural element also includes dead load and portion of live load that it carries. While these loads could be estimated fairly accurately, the calculation of the earthquake action depends on many factors, such as the following:

1. Importance level of the structure. This classification depends on the functional type of the building.
2. Annual probability of exceedance of the earthquake event which is based on the importance level of the structure.
3. Hazard factor which is determined by the geographical location of the building.
4. Site sub-soil class that is determined using bore logs, measurement of shear-wave travel time through material from the surface to underlying rock, actual recorded earthquake motions, etc.
5. Earthquake design category which establishes level of complexity of analysis to be carried out. Depending on all four factors mentioned above, the method of analysis may require a minimum static check, equivalent static analysis or dynamic analysis.

3 DYNAMIC ANALYSIS APPROACH

3.1 INTRODUCTION

This section details the general steps involved in seismic dynamic analysis modelling to satisfy AS1170.4-2007. This approach focuses on three-dimensional analysis using today's commercially available FEM software such as Strand-7, ETABS, ROBOTS, etc.

3.2 THREE-DIMENSIONAL MODELLING

The first step is to construct a three-dimensional model using FEM software. In principal, only structural elements with significant stiffness and ductility should be modelled. Generally only concrete members are modelled whilst steel members with minuscule stiffness are ignored. Non-structural components which do not participate in lateral resisting can also be neglected. Floor members such as slabs are modelled as rigid-in-plane diaphragm plate elements.

The mass of the structure was verified by manual load take down calculation. The computer model was also checked for the boundary conditions and equilibrium with simple static load pattern.

3.3 FREQUENCY ANALYSIS

Most FEM softwares have built-in features to carry out frequency analysis. The first mode from the output is the fundamental/natural frequency of the structure. This value is generally used in calculating the earthquake action for static analysis.

Furthermore, the strings of the frequencies generated would be used in calculating the response for modes of vibration in modal-response-spectrum analysis.

3.4 THREE-DIMENSIONAL MODE SHAPES AND MODAL-RESPONSE-SPECTRUM ANALYSIS

Generally, dynamic analysis can be performed either by modal-response-spectrum analysis or time-history analysis.

Modal-response-spectrum analysis is more common and it is utilised by almost every modern design code. This analysis requires a curve that defines the spectral acceleration in terms of building's period. In the design codes, the values of the response spectrum curves are always normalised using non-dimensional values. There is a scaling factor, which multiplies the values on the vertical axis of the curve. After scaling, these values would have the dimensions of acceleration.

Most FEM software has a built-in response spectrum curve to the national codes. For example, Strand7 has built-in curves for the Australian Standard.

Dynamic analysis by this modal-response-spectrum method should adopt the peak response of all modes that have significant contribution to the total structural response. Common practice is to include sufficient modes in the analysis so that at least 90% mass of the structure is participating for the direction under consideration. In addition, all modes with period less than 5% of the fundamental natural period of the structure may be ignored.

The two well-known methods in combining the modes for working out the earthquake forces, member displacements and base reaction of each mode are square-root-of-sum-of-squares (SRSS) and complete quadratic combination (CQC). Wilson (1998) suggests that the CQC method is superior to SRSS in three-dimensional analysis as it eliminates problems associated with closely spaced periods.

As for the time-history analysis, the method requires the data which represent the actual earthquake motions. These earthquake records might not be readily available for all the areas.

3.5 EARTHQUAKE ACTION

According to AS1170.4-2007, the horizontal design response spectrum ($C_d(T)$) based on modal-response-spectrum analysis is calculated as follows.

$$C_d(T) = C(T)\, S_p/\mu \qquad \textbf{(3)}$$

$$= C_h(T)\, k_p\, Z\, S_p/\mu \qquad \textbf{(4)}$$

where $C(T)$= value of elastic site hazard spectrum, $C_h(T)$ =value of spectral shape factor for the given period of vibration, k_p = probability factor for the given annual probability of exceedance, Z = hazard factor for specific Australian location, S_p = structural performance factor, μ = structural ductility factor

The formula above is similar to the calculation of horizontal design action coefficient of static analysis. The main different is the site hazard spectrum, C(T) is based on period of vibration (T) appropriate for the particular mode of vibration rather than the single design value obtained from the fundamental natural period.

3.6 TORSION EFFECTS

Accidental torsion due to uncertainties in the distribution of live load mass and the stiffness variation of structural properties need to be added to the analysis. For three-dimensional dynamic analysis, the additional torsional loads can be accounted for by adjusting the mass location.

The current code also allows the use of static analysis by applying horizontal forces offset from the centre of mass at each floor. The equivalent pure torsional loads produced are then applied at the centre of mass. This set of torsional loads needs to be kept as a separate load case so that it may be combined with other static or dynamic loads to produce the worst case effects in the resisting members.

4 APPLICATION FOR HOSPITAL BUILDING

4.1 STRUCTURAL FORM OF ACUTE CARE HOSPITAL

The general building form was determined by functional and architectural planning requirements with a general building footprint of approximately 145 m x 105 m. Architectural planning requirements have located a number of service cores (lifts, stairs, etc) within a central spine of the building and a number of emergency stair cores located at the periphery of the building.

The structural grid adopted to meet the functional and architectural planning constraints of the building form is based on a modular planning grid of 600 mm and has been chosen at 10.8 m x 7.2 m and 10.8 m x 8.4 m.

To achieve current functional requirements a 4.2 m floor-to-floor height was adopted for the building and the basement had been set at 5.2 m to meet future flexibility at this level.

The building will be 9-storey, with 2 additional storeys to accommodate future growth of medical and associated facilities. The ultimate height of the structure with these additional floors will be 48 m. This will require vertical elements, i.e. columns, walls and foundation to be designed for anticipated additional loads.

Summary of the structural system are as follows.

1. Typical floors are post-tensioned reinforced slab with band beams system.
2. The building adopted a reinforced concrete braced frame structure which consists of rectangular/square columns to support vertical loads and reinforced shear walls within lift/stair cores to provide lateral stability.
3. The building superstructure is characterised by large floor plates which reduce in size at higher levels.
4. All building foundations are founded on minimum Class III shale bed rock to eliminate the need for ground beams.

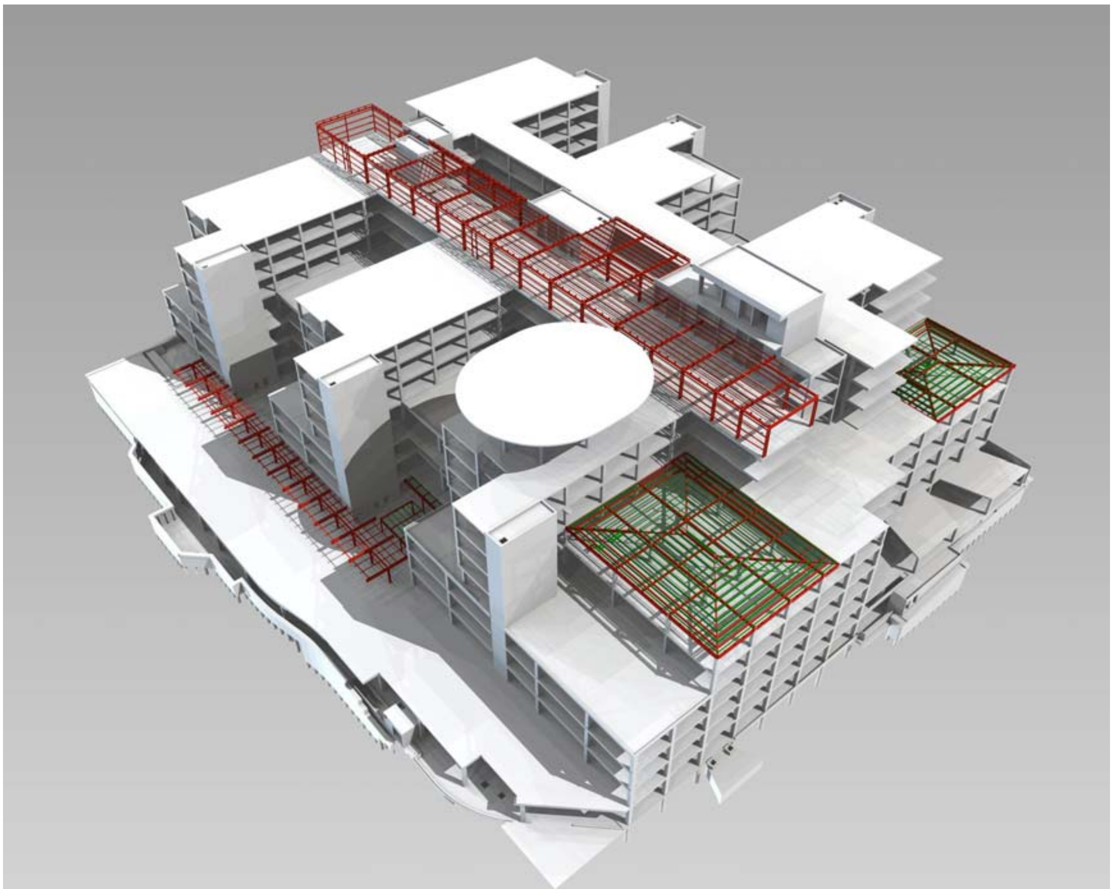


Figure 1: Building Information Model (BIM) of Acute Care Hospital Structure.

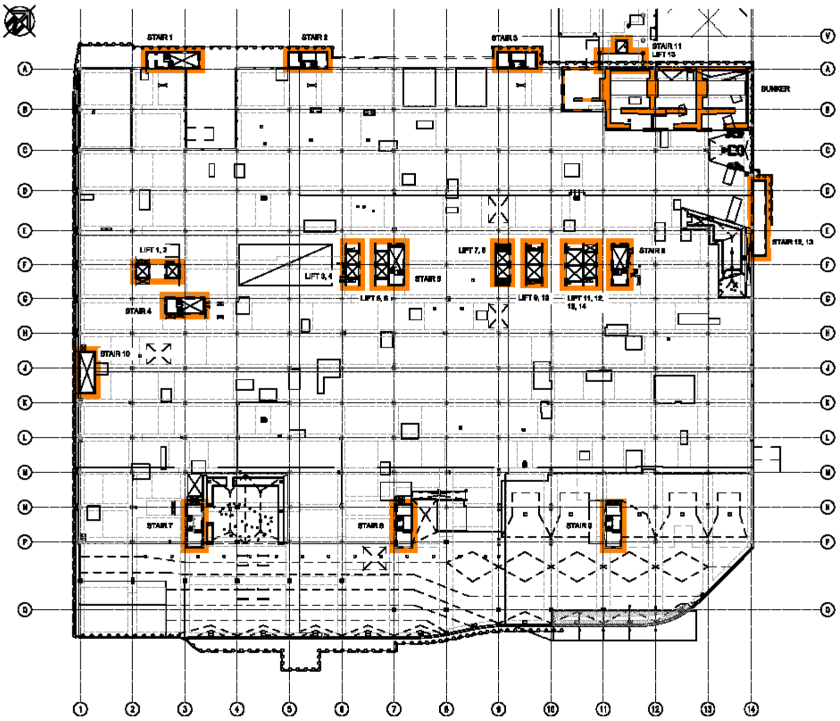


Figure 2: Level 2 floor plan, highlighting major shear walls in the building

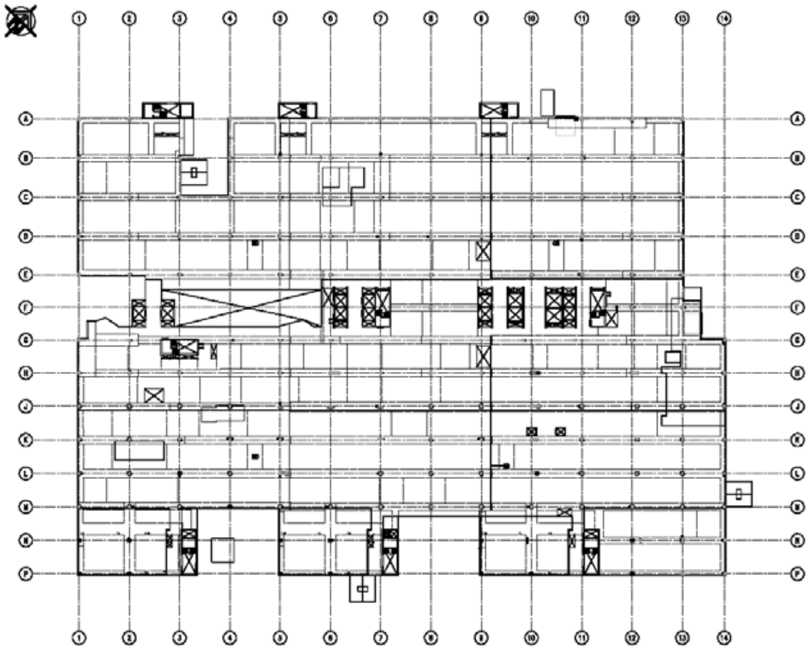


Figure 3: Level 5 with reduced floor plan size

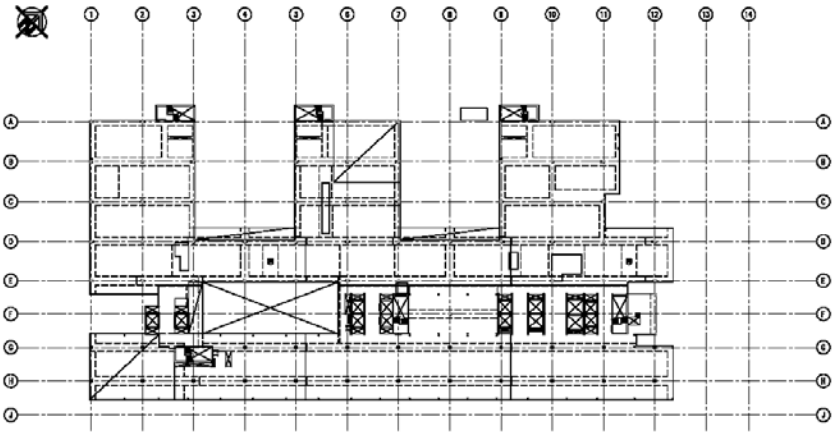


Figure 4: Level 9 floor plan

4.2 EARTHQUAKE DESIGN CATEGORY

Summary of the determination of earthquake design category based on the importance level of the structure, probability factor, hazard factor and site sub-soil class for Acute Care Hospital are shown on Table 1.

Table 1: Seismic Analysis of Acute Care Hospital to AS 1170.4-2007

Criteria	Design Value	Comments
Importance level of the structure	Level 4	Building or structure that is essential to post-disaster recovery
Probability factor (kp)	kp = 1.50	Structure with a 1:1500 year annual probability of exceedance
Hazard factor (Z)	Z = 0.08	The building site is located in Sydney
Site sub-soil class	Class Be - Rock	Based on the bore logs, the site sub-soil is characterised with shale/weathered shale with compressive strength between 1 and 3 MPa
Earthquake design category (EDC)	EDC III	Combination of importance level 4 structure and building height of more than 12 m

4.3 THREE-DIMENSIONAL FEM

A combination of plate and beam elements has been used to construct the model of the building. The columns and beams have been modelled using beam elements while the slab, stair cores and lift cores have been modelled using plate elements.

Core walls as the primary earthquake resistant components are modelled with refined mesh in order to obtain an accurate stress distribution on the members.

Vertical setback at higher levels and building re-entrant are modelled as close as possible to the real structure in order to capture the irregularity on plan and any real torsional effects that might occur.

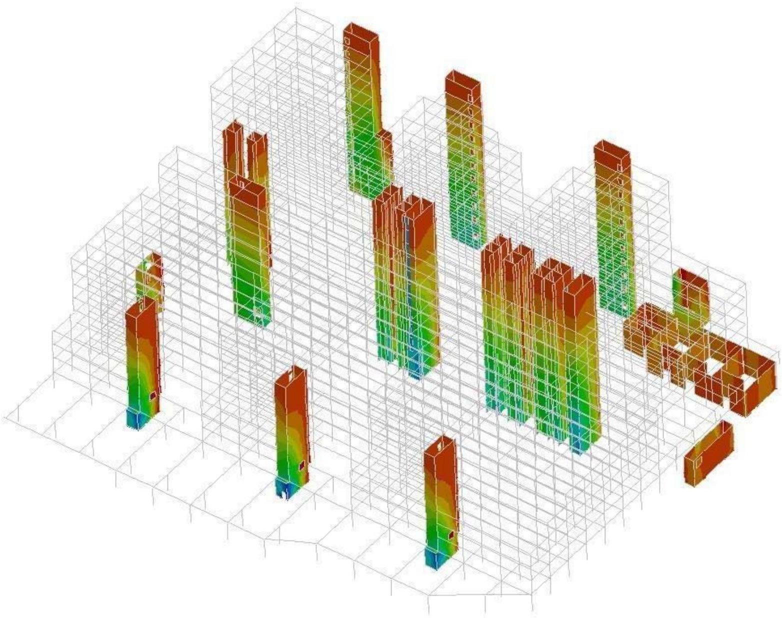


Figure 5: Major Shear Walls from Strand7 Model.

4.4 MODAL-RESPONSE-SPECTRUM AND FREQUENCY ANALYSIS

The first step in the dynamic analysis is to calculate the natural frequencies of vibration and the three-dimensional mode shapes together with the corresponding participating mass in two orthogonal directions.

Table 2: First 10 modes of natural frequency for the building calculated using Strand7.

STRAND 7 OUTPUT		
Mode	**Frequency (Hz)**	**Period (sec)**
1	0.961	1.041
2	1.037	0.965
3	1.215	0.823
4	2.595	0.385
5	2.924	0.342
6	3.285	0.304
7	3.575	0.280
8	3.662	0.273
9	3.725	0.268
10	3.809	0.263

The current code provides an empirical method for estimating natural period to be used in static analysis. The manual calculation for the first natural period based on this method gave $\mathbf{T_1 = 1.125\ s}$. Hence, both empirical method and computer model yield the first natural period of around 1 second.

The table above shows that most of the periods are closely spaced. This is generally the case for a structure with similar stiffness in all directions.

The mass participation of the first 10 modes is presented below.

Table 3: Mass Participation in modal-spectrum-analysis

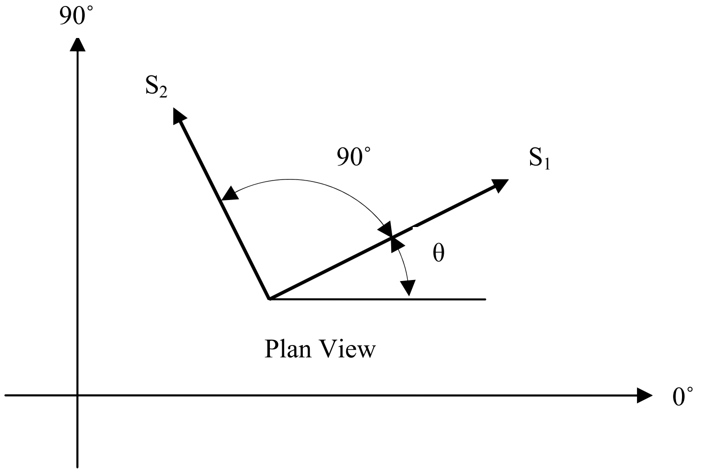
Mode	**x-direction (%)**	**y-direction (%)**	**x-direction sum (%)**	**y-direction sum (%)**
1	5.393	41.560	5.393	41.560
2	55.402	5.344	60.795	46.904
3	0.534	12.526	61.329	59.430
4	3.660	0.968	64.989	60.398
5	3.631	1.614	68.620	62.012
6	6.792	13.818	75.412	75.830
7	0.001	0.000	75.413	75.830
8	3.039	3.365	78.452	79.195
9	3.527	2.405	81.979	81.600
10	0.029	0.163	82.008	81.763

The first 10 modes gave over 80% of mass participation. Some modes that did not provide significant contribution to the seismic resistant system shall be excluded. As shown above, mode no. 7 and no. 10 contributed very little to both x and y direction hence should be ignored when combining the modes to produce dynamic earthquake load. In order to satisfy at least 90 percent of the participating mass for each direction, 50 modes were required.

4.5 DYNAMIC EARTHQUAKE ACTION

The current code provides minimum coverage on how to translate modal-response-spectrum analysis results into the design loads on the structure. In addition it does not explain which direction or combination of directions to which the earthquake load should be applied.

For this project, complete quadratic combination (CQC) was used to combine the participating modes in the two separate spectrum analyses applied in the major and minor principal directions. Wilson (1998) defines the major principal direction for three-dimensional structure as the direction of the base shear related to the fundamental period whereas the minor principal direction is ninety degrees apart from it.



Note: S_1 and S_2 are the corresponding principal directions of the structure.

Figure 6: Definition of Principal Directions by Wilson (1998)

For this structure, the principal directions are oriented at 115˚ and 205˚.

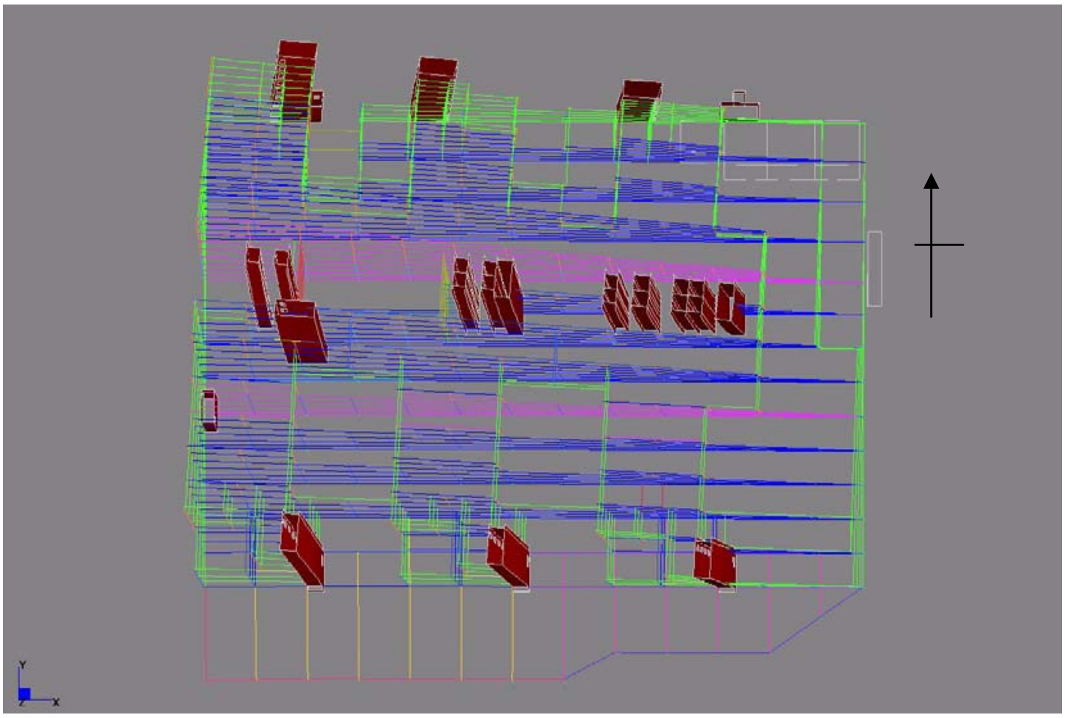


Figure 7: Mode-1 Deformation on the Major Principal Direction

As shown above, mode-1 indicated building movements in both the Northwest and Southeast directions. The major principal direction of the earthquake therefore follows this fundamental mode of vibration with the exact angle being 115˚ anticlockwise for Northwest displacement or -65˚ clockwise for Southeast displacement. This direction is nearly perpendicular to the 'strong' axis for majority of cores, mostly located at the central and south regions. In-plane irregularities characterised by vertical set-back and re-entrant corner plans also introduce torsion with increase significant at the higher levels as the floor plate reduces in size.

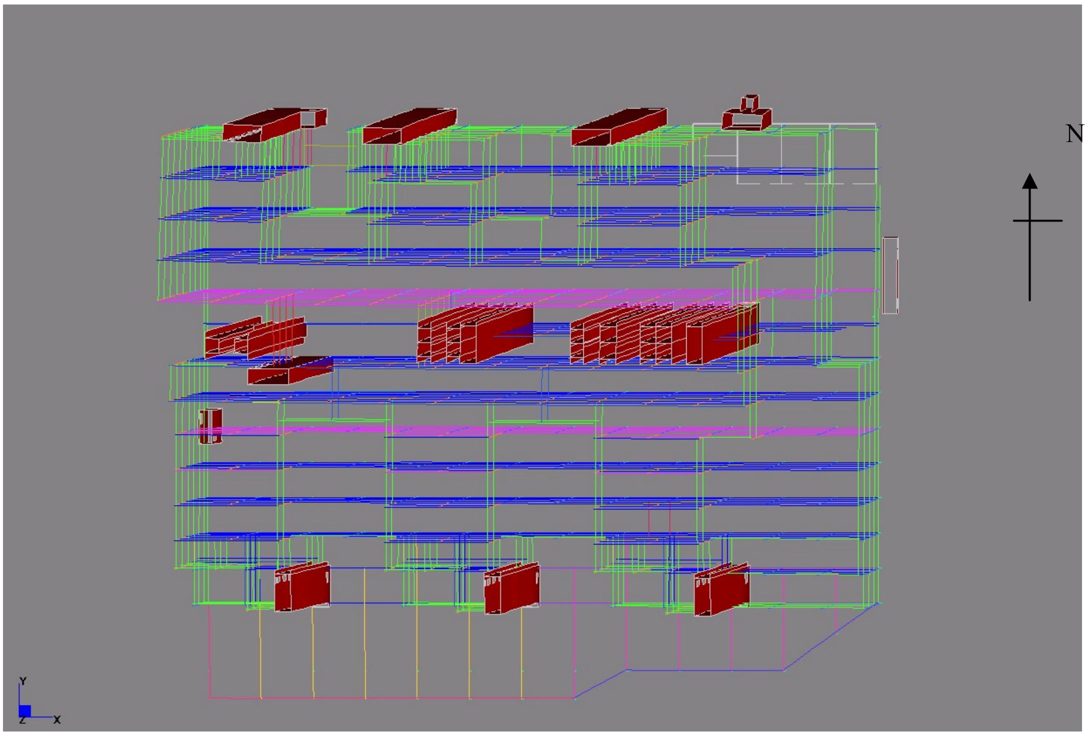


Figure 8: Mode-2 Deformation on the Minor Principal Direction

Mode-2 displacements occurred at the angle of 205˚ and 25˚, with both being 90˚ apart from the mode-1 displacements. Once again, this direction is almost perpendicular to the 'weak' axis for central and south cores. This mode does not experience significant torsional rotations on the floor plane.

Applying horizontal design response spectrum ($C_d(T)$) as described previously on Section 3.5 to the results of modal-spectrum-analysis in both principal directions yield the following base reactions.

Table 4: Dynamic Base Reactions using CQC Method

Principal Direction	**Base Shears (MN)**		**Overturning Moments (MNm)**
	$V_{(115^\circ)}$	$V_{(205^\circ)}$	M_z
Major axis (115˚)	16.0	0.04	342
Minor axis (205˚)	0.25	21.3	512

As can be seen, the major reaction is in the direction of the seismic input whereas insignificant reaction is observed on the direction normal to the direction of the loading. This output confirms that the directions of 115˚ and 205˚ are a good definition of the principal directions of this structure.

4.6 STATIC EARTHQUAKE ACTION AND RESULTS SCALING

The base reactions calculated by using equivalent static analysis are as follows.

Table 5: Static Base Reactions

Principal Direction	**Period (s)**	**Base Shears (MN)**	**Overturning Moments (MNm)**
Major axis (115˚)	1.041	26.7	720
Minor axis (205˚)	0.965	28.6	772

The current AS1170.4-2007 has omitted the requirement to scale the results from the dynamic analysis. However, as the calculated base shear from dynamic analysis is much lower than static analysis, hence the writer has scaled up the dynamic base shear to 80% of the value calculated by using static analysis. This is basically the lowest possible value that is permitted by the superseded AS1170.4-1993.

As pointed out by Ghosh (2003), scaling up the dynamic analysis results with respect to the results obtained from equivalent static analysis is crucial in ensuring that the design forces are not underestimated through the use of a structural model that is excessively flexible.

Previous section demonstrates that the period obtained by FEM is really close to the value calculated manually suggesting that there is a good agreement between the rigorous method of analysis and empirical prediction. It also serves to confirm that the model's stiffness is within the empirical expectation for the given structure height, hence confirming that the approach to adopt minimum 80% base shear is conservative.

Table 6: Scaled Dynamic Base Reactions using CQC Method

Principal Direction	**Scaled Base Shears (MN)**	**Scaled Overturning Moments (MNm)**
	V	M_z
Major axis (115˚)	21.4	455
Minor axis (205˚)	22.9	550

4.7 COMPARISON TO STATIC ANALYSIS

Results from dynamic analysis may differ from static analysis in terms of the force distribution among the building elements. More importantly, dynamic analysis produces a more accurate representation of the building behaviour under seismic load.

The lateral resistant elements in the Acute Care Hospital are spread across the multiple core walls located mainly on three regions of the building, namely north, central and south regions. Loads resisted by each group of core walls were determined by its location, stiffness and the connection to the building. Observation was made on the force distribution among the cores due to earthquake in major axis. The proportion of cores' base shears calculated using static and dynamic analyses are presented below.

Table 7: Comparison of Force Distribution due to Earthquake on the Major Axis

Core Location	***Static Analysis % Base Reaction***		***Dynamic Analysis % Base Reaction***	
	Major Axis	***Minor Axis****	***Major Axis***	***Minor Axis****
North Cores	34%	15%	30%	-48%
Central Cores	31%	40%	30%	40%
South Cores	35%	-55%	40%	8%
Sum	100%	0%	100%	0%

** Note: This percentage is calculated based on the proportion of the base reaction to the absolute sum of total reaction. Negative value indicates opposite direction of the reaction.*

The earthquake force applied to the major axis results in base shears on this axis of the seismic input and the axis normal to the direction of the loading, i.e. minor axis. There was a good agreement for the reaction on the major axis between two analyses. However, significant differences were shown on the minor axis in both magnitude and direction. For static analysis, base shears were experienced by the north and central cores in one direction and the south cores in the opposite direction. On the other hand, dynamic analysis indicated that both central and south cores were loaded in one direction and north cores in the opposite direction. These effects are mainly generated by the torsional rotation of the building that accompanies the main lateral displacement. Careful examination on the building geometry and core wall configuration revealed that dynamic analysis provided the correct output. As the centre of stiffness of each floor was mostly located in the area around central and north cores, it is to be expected that central, south cores will provide resistance in one direction and will be opposed by the north cores that are significantly stiffer on the minor axis.

4.8 TORSION EFFECT

For this project, the incidental torsion is taken into account by using static torsional load. The current code allows the use of horizontal equivalent static load with vertical load distribution applied at design eccentricity from the building centre of mass. The offset magnitude from the nominal centre of mass is taken as ±10% of the plan dimension of the structure at right angles to the direction of action. The equivalent pure torsional static loads are then applied at the centre of mass at each floor.

These torsional loads are translated as additional base shears and overturning moments experienced by the core walls. Depending on the direction of earthquake and the offset orientation from the building centre of mass, there are essentially 4 load cases that need to be considered.

1. Clockwise torsion due to earthquake on the major axis
2. Anticlockwise torsion due to earthquake on the major axis

3. Clockwise torsion due to earthquake on the minor axis
4. Anticlockwise torsion due to earthquake on the minor axis

The summary of base shear distribution due to torsion in the major axis direction of applied earthquake load is shown on the following table.

Table 8: Comparison of Force Distribution due to Earthquake in Major Axis

Core Location	**Clockwise Torsion Major Axis % Base Reaction***	**Anticlockwise Torsion Major Axis % Base Reaction***
North Cores	-54%	55%
Central Cores	14%	-13%
South Cores	40%	-42%
Sum	0%	0%

** Note: This percentage is calculated based on the proportion of the base reaction to the absolute sum of total reaction. Negative value indicates opposite direction of the reaction*

The major resistance to the rotation comes from the north cores in one direction and is opposed by the rest of the cores located in the central and south regions.

4.9 MEMBER DESIGN FORCES

The design load for lateral resistant members is described in Equation **(2)** being the combination of vertical and earthquake load. The design earthquake load consists of dynamic force and accidental torsion load. Each core is analysed for the two principal directions plus clockwise or anticlockwise torsion force which increases the value of force. It is observed that the worst case scenario for typical core is the earthquake in the direction nearly perpendicular to its major axis where the core is stiffer, hence attracting higher base shear and overturning moment. The cores along the perimeter of the building experience a higher load as they need to resist the majority of additional load due to torsional moments.

5 CONCLUSIONS

This paper has outlined the general earthquake design criteria for hospital building and principles of using FEM software to assist in carrying out seismic dynamic analysis according to Australian Earthquake Design Code AS 1170.4-2007. The major steps involved in the approach are as follows.

1. Using FEM software, a three-dimensional model is set up. This model shall include all significant structural elements that will affect the building behaviour and more importantly those participating in lateral resisting system.

2. The next step is to run natural frequency analysis. The fundamental natural frequency gives an indication of the flexibility of the structure and determines the level of design earthquake force.

3. Combining the results from natural frequencies and the response spectrum curves, modal-response-spectrum analysis is carried out. Only modes that form part of the seismic-force-resisting system are to be included. These are the modes that provide significant mass participation. It is also recommended to include sufficient number of modes with common practice of minimum 90% of the mass participating for the direction under consideration. The output from modal-response-spectrum analysis provides insight into the directional and torsional characteristics of the building.

4. The two horizontal directions of the base shear are determined by mode shapes of the building. The major principal horizontal direction is to follow the direction of first mode and subsequently minor principal direction is on the second mode.

5. Dynamic forces are produced by combining the modes using methods such as square-root-of-sum-of-squares (SRSS) or complete quadratic combination (CQC) in both principal directions.

6. Equivalent static analysis is performed to produce static design loads in both principal directions. If the design forces obtained by dynamic analysis are significantly lower than those from static analysis, it is recommended to consider scaling up the load based on the base shear’s ratio.

7. Incidental torsion needs to be included either by adjusting the mass location or by equivalent static procedure. The latter approach is more practical for the application on a complex three-dimensional model. Torsion static load is produced by using the vertical distribution force obtained from static analysis applied at offset distance from centre of mass. The design earthquake force should only consider the torsion in the direction that leads to the increase of the force.

6 REFERENCES

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