Research news and notes

SOME LIMITATIONS OF MODAL ANALYSIS IN SEISMIC DESIGN

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1. Synopsis

In the normal-mode, response-spectrum approach to earthquake resistant design of multistorey buildings the extended elastic seismic design loads are frequently calculated as the square root of the sum of the squares of the modal responses. The individual member forces are then determined using these seismic design loads. Previous research workers have examined the limitations of this technique and it is accepted as being generally applicable in practical design procedures.

Recent computer analyses of projected New Zealand high-rise buildings have illustrated two conditions in which the 'square root of the sum of the modal responses squared' rule is inapplicable.

In this note these situations are described and suggestions are made of an alternative approach which may be adopted when deriving design loads in such cases.

2. Introduction

The normal-mode, response-spectrum technique[1,2] has been applied successfully, so far as can yet be ascertained, to the seismic design of many high-rise buildings including several New Zealand ones[3,4,5].

In their report[6] on methods of mode combination, Merchant and Hudson concluded that a suitable weighted average of the sum of the absolute values of the individual modes and the square root of the sum of the squares of the modes will give a practical design criterion for the base shear forces in multistorey buildings. They pointed out that for critical cases, the weighted average reduces to the absolute sum of the modes.

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Skinner[1] has proposed a simple approximate rule for combining the maximum earthquake responses of the normal modes, namely to compute the square root of the sum of the squares of the values for the individual normal modes. Comparison of the results obtained using this approach with those calculated by direct integration of the equation of motion have shown that for many practical design cases Skinner's simple approximation is entirely adequate.

However two recent computer analyses of projected buildings have illustrated that application of the simple combination rule can prove misleading in certain circumstances. These are described below.

3. The Buildings and the Problems

The first high-rise building analysed had a flexible reinforced concrete frame, fourteen storeys high and three bays by four bays on plan. Its symmetry made torsional considerations unnecessary.

The computed dynamic properties are listed in the accompanying table.

Direction	Mode	Period (Seconds)	Earthquake Amplification Factor (10% Critical Damping)
Longitudinal	1	1.28	0.28
Transverse	1	1.38	0.26
Longitudinal	2	0.45	0.70
Transverse	2	0.49	0.67

The computed 1g storey forces in the first mode were comparable with those in the second mode except just above and below the upper node point in the higher mode.

On multiplying by the earthquake amplification factor the second mode forces were predicted to be some 2.5 times greater than the first mode forces.

When the square root of the sum of the modal responses squared was computed, the second mode positive and negative storey forces accumulated towards the base of the building and hence the second mode response completely dominated the seismic load determination process.

The design shears so established were considered to be of very little value. A factor of about eight was needed to reduce the base shears to the code requirements[7].

In this case the problem was overcome by reverting to a direct integration procedure. The variation of the seismic forces with respect to time at each floor was established for a chosen (El Centro) digitised earthquake record. It was found that the worst cases of loading occurred over a relatively short time interval and so a static load analysis was undertaken assuming the worst case loading occurred at each floor simultaneously.

The resulting member forces were only about half those derived from the modal analysis approach and a factor of about four was found necessary to reduce the base shears to the code requirements.

The second high rise building analysed comprised a reinforced concrete composite tower and frame structure of nine storeys. The two towers and the four perimeter frames were not symmetrically placed and so torsion had to be considered. This in itself did not pose any special problems since the analysis technique has been well developed[8,9].

The fundamental period of the building was computed to be about 0.4 seconds and so the higher modes could not have the predominating effect which they had in the case of the first building referred to above. In this second structure it was the interaction between the elements which caused considerable difficulty in substantiating the analysis procedure initially used.

As the frames and towers suffered overall lateral displacements, in resisting the lateral loading, it was evident from the modal analyses' results that in addition to the forces necessary in the main structural elements to resist the external loading, extra loads existed because of the interaction of the elements on each other.

This additional effect was emphasised by the existence of both positive and negative first mode forces in the resisting elements.

On taking the square root of the sum of the modal responses squared, the sense of the component forces was lost and so all the storey forces accumulated down the building to produce relatively large base shears.

In the case of one element the 'square root of the sum of the squares' base shear proved to be five times the first mode base shears.

The desirability of avoiding the situation in which component elements can fight between themselves when responding to lateral loads was very clearly illustrated in this design. Nevertheless in this particular case a solution to the analysis problem had to be found. The necessity to consider torsional effects precluded a direct integration solution for this building.

Instead the following approach was adopted. A series of static analyses were undertaken to determine the element member actions corresponding, for each mode, to the 1g modal shears multiplied by the appropriate earthquake amplification factor. The overall member actions were then computed as the square root of the sum of the squares of the modal member actions.

The pattern of member actions so computed was significantly different from that obtained from the 'square root of the sum of the squares of the modal storey forces' approach. Those total responses which had previously appeared unjustifiably large were reduced by a factor of between 2.5 and 3.0 on recalculation and this much more reasonable set of member actions was judged to be of value in the subsequent seismic design process.

4. Conclusion

The two instances described above illustrate that the generally satisfactory 'square root of the sum of the modal responses squared' rule is not always applicable. As long as designers appreciate that limitations on its use do exist it will still be used in the majority of extended elastic seismic design calculations.

The object of this note is to draw attention to two circumstances in which its use on the modal forces leads to erroneous conclusions.

5. References

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