Non-Linear Response of Electrical Cubicles for Fragility Estimation

J. M. Llambias, C. J. Sevant, D. J. Shepherd
National Nuclear Corporation Ltd., Knutsford, Cheshire, UK

1 INTRODUCTION

A review of seismic probabilistic safety assessments carried out for nuclear power stations shows that electrical cubicles feature as a dominant contributor to the seismic risk in a considerable number of the stations. The seismic fragility for an electrical cubicle is normally taken to be relay failure, whether by trip or chatter, as relay failure occurs at much lower accelerations than structural failure of the cubicle itself. Hence a good understanding of the seismic response of the cubicle, and in particular the in-structure amplification, is required to produce realistic fragility parameters.

To this end, the behaviour of typical electrical cubicles under seismic excitation was examined both experimentally and theoretically. This paper summarises the work carried out.

2 DESCRIPTION OF ELECTRICAL CUBICLES

A suite of two electrical cubicles were examined in this work. Each cubicle was 2.4 m high, 0.6 m wide and 0.57 m deep, and weighed approximately 525 kg. The cubicles, which were of the type used in UK PWR power stations, were bolted together at the top and bottom to form a typical motor control centre, see Fig. 1.

3 EXPERIMENTAL WORK

The two cubicles were extensively instrumented with accelerometers to enable detailed response information to be extracted from the testing. The cubicles were subjected to two sets of tests during the experimental work. These were modal tests and seismic fragility tests.

During the modal testing, both impact resonance testing and shaker table testing using narrow band random excitation were carried out. The shaker table testing was carried out using excitation over a 1 to 100 Hz band width at five amplitude levels up to 0.5 g. The structural responses recorded by the accelerometers were processed and the modal properties obtained are summarised in Table 1(a).

During the seismic fragility testing, the cubicles were subjected to increasing levels of random excitation representative of a range of UK sites. The excitation levels were increased to levels at which significant structural damage was expected. The structural response was recorded at the base of the cubicles and at various locations on the trays within the cubicles. Vertical response data was recorded at both the centre and edges of the trays whilst horizontal response data was recorded only at the edges of the trays. Typical recorded response spectra are given in Fig. 2.

The results of the seismic fragility testing indicated also that as the excitation level increased the natural frequency of the cubicles decreased. This variation in the natural frequency of the cubicles with excitation level was calculated from the measured response and the results are given in Table 2.

4 THEORETICAL WORK

4.1 Structural Idealisation

In the theoretical work only one cubicle was modelled in detail. The second cubicle comprising the motor control centre was represented using constraint equations. This was done with a view to develop a simple and cost-effective procedure to examine the seismic response of any number of cubicles, all bolted together in series, by the use of constraint equations.

The detailed model of the electrical cubicle consisted of an assemblage of beam and thin shell finite elements representing the main features of the cubicles including the drawers, seismic support plates and covers. Substructuring techniques were used to incorporate the effects of the gussets located at the bottom corners of the cubicle. The finite element model of the cubicle is shown in Fig. 3.

4.2 Modal Analyses

The modal analyses of the cubicles were carried out using the general purpose finite element program, ANSYS. The natural frequencies and mode shapes for both a single cubicle and the combination of the two cubicles were calculated and the results are shown in Tables 1(a) and 1(b). These tables show only horizontal modes of vibration. The analyses showed that the cubicles were seismically rigid in the vertical direction.

5 DISCUSSION OF RESULTS

Table 1(a) compares the calculated natural frequencies for the combination of two cubicles with those obtained from the modal testing. This table shows a good comparison between experimental and analytical results which thus gives confidence to the use of constraint equations to represent a combination of two or more cubicles bolted together in series. Also, both experimental and analytical results indicated that the cubicles were seismically rigid in the vertical direction.

However, the natural frequencies quoted in Table 1(a) are only valid for low levels of excitation. The seismic fragility testing indicated that as the level of excitation increases, the natural frequency decreases as shown in Table 2. This decrease in the natural frequency was due to the non-linear dynamic response of the cubicles to high excitation levels.

This variation in the first mode natural frequency of the cubicles with excitation level can be predicted by a simple model comprising a rigid beam with a uniformly distributed mass on a rotational spring and damper system. This indicates that the first mode of vibration in the two horizontal directions was purely a rocking mode and that the non-linearities were associated with the base of the cubicles. This simple model was used also to estimate the modal damping from the measured response of the cubicles. The calculated damping is shown in Table 2.

Table 2 shows that for side-to-side rocking, the natural frequency decreases with excitation level but the damping remains constant. The decrease in the natural frequency is due to a reduction in stiffness and this is supported by the results of the visual inspections of the cubicles which were carried out after each test. The inspections showed yielding of the gusset plates at the bottom corners of the cubicles. The big reduction in the natural frequency between excitation levels of 75% and 100% RRS* was due to the substantial decrease in stiffness as a result of the tearing of the gusset plate at the higher excitation level.

A similar reduction in the natural frequency is shown for rocking in the foward-aft direction. Visual inspections showed that in this case, the reduction in stiffness was due to the yielding of the plinth fixing the cubicles to the floor. The increase in the damping can be attributed also to this yielding, which was much more evident on the plinth than on the gusset plates. In particular, the big increase in damping between excitation levels of 100% and 125% RRS is supported by the results of the visual inspection carried out after the higher level tests which indicated that buckling of the plinth had occurred.

For higher modes of vibration (frequencies above 16 Hz), the experimental work indicated that non-linear effects due to rattling and impacting between the cubicles and the components within the cubicles were evident. Hence, it was not considered to be possible to examine the high frequency response (greater than 16 Hz) response of the cubicles using a simple model.

5.1 Examination of In-structure Amplification

As mentioned earlier, the seismic fragility of an electrical cubicle is based on failure of one of the electrical components within it, i.e. relay failure. Hence, it is necessary to examine the in-structure amplification, i.e. the spectral response at the component location relative to the spectral response at the base of the cubicles, in order to estimate the fragility parameters for the cubicles.

The examination of the in-structure amplification was based on the results from the seismic fragility testing. The spectral amplification factors at the different excitation levels were calculated by dividing the recorded acceleration response spectra at the various tray locations by the corresponding recorded spectrum at the base of the cubicles. A typical 'smoothed' amplification spectrum in the horizontal direction is shown in Fig. 4. All amplification spectra, both in the horizontal and the vertical directions, showed a similar trend with a 'plateau' above 16 Hz.

The estimation of the fragility parameters for the cubicles requires the in-structure amplification to be described in a probabilistic manner. This involves the determination of a best-estimate value for the median amplification factor ($\check{F}$) for a range of tray locations and excitation levels, together with a measure of the randomness (βr) and uncertainty (βu) associated with this median value. The distribution parameters βr and βu are lognormal standard deviations from the median amplification factor.

In this study, it was considered appropriate to use the 'plateau' region of the amplification spectra to calculate the best-estimate amplification factors. The median amplification factor corresponding to the 'plateau' region was determined for each location at all excitation levels. Then following a statistical approach illustrated in NUREG/CR-4900 (Holman, 1987), best-estimate median values for the amplification factors together with their distribution parameters were obtained. The results are shown in

*RRS - Typical Required Response Spectra covering a range of UK sites

Table 3.

Using the results shown in Table 3, and with a knowledge of the failure levels for electrical switchgear within the cubicles, then the seismic fragility parameters for electrical cubicles can be estimated.

6 CONCLUSIONS

This paper has summarised the work carried out to examine the seismic response of typical electrical cubicles for fragility estimation.

At low levels of excitation, the experimental and theoretical work predicted similar natural frequencies and mode shapes for the electrical cubicles. The theoretical method employed can be extended to examine the natural frequencies and mode shapes for any number of cubicles bolted together in-series.

At higher levels of excitation, the cubicles behaved in a non-linear manner. It was possible to predict the first natural frequency and mode shape at different excitation levels using a simple model. The simple model indicated that for the first mode of vibration, the non-linearities were associated with the base of the cubicles, i.e. the stiffening gusset plates and the plinths. Above 16 Hz, the non-linear effects due to rattling and impact were evident in the experimental work.

Finally, the in-structure amplification was examined and best-estimate median amplification factors together with their corresponding distribution parameters were derived. These parameters were in a form suitable for fragility estimation.

ACKNOWLEDGEMENT

The Authors wish to thank the National Nuclear Corporation Limited for permission to publish this paper.

REFERENCES

Holman G. S. and Chou C. K., (1987), 'Component Fragility Research Programme - Phase 1, Demonstration Tests, Volume 1: Summary Report', NUREG CR-4900

Table 1(a)

Comparison of Natural Frequencies Obtained from Analysis and Testing for the Motor Control Centre (Two Cubicles Bolted Together)

Mode Number	Natural Frequency (Hz) Analysis	Test	Mode description
1	6.0	6.3	Rocking in the side-side direction
2	9.0	9.2	Rocking in the foward-aft direction
3	20.1	-	Bending in the side-side direction

Table 1(b)

Predicted Natural Frequencies for a Single Electrical Cubicle

Mode Number	Natural Frequency (Hz)	Mode Description
1	5.1	Rocking in the side-side direction
2	9.0	Rocking in the foward-aft direction
3	18.9	Bending in the side-side direction

Table 2

Variation in Rocking Natural Frequency and Damping with Excitation Level

Excitation Level (% RRS)*	Side-Side		Foward-Aft	
	Natural Frequency (Hz)	Damping Ratio	Natural Frequency (Hz)	Damping Ratio
50	4.4	0.24	9.3	0.18
75	4.1	0.24	8.6	0.19
100	2.7	0.24	7.7	0.20
125	-	-	6.6	0.25

*RRS : Typical Required Response Spectra for a range of UK sites

Table 3

Summary of Amplification Factors and Their Corresponding Distribution Parameters

Direction	Location on Tray	Amplification Factor $\check{F}$	Distribution Parameters	
			β_r	β_u
Horizontal	Any	1.8	0.3	0.03
Vertical	Edge	2.2	0.2	0.03
Vertical	Centre	3.9	0.3	0.03

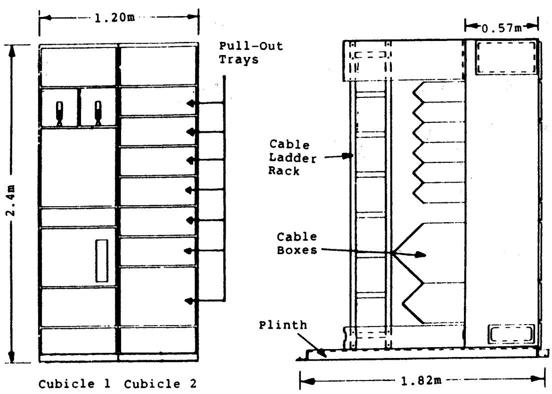

Figure 1 : Typical Electrical Cubicles

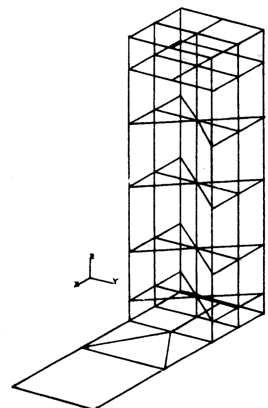

Figure 3

Finite Element Model of Cubicle

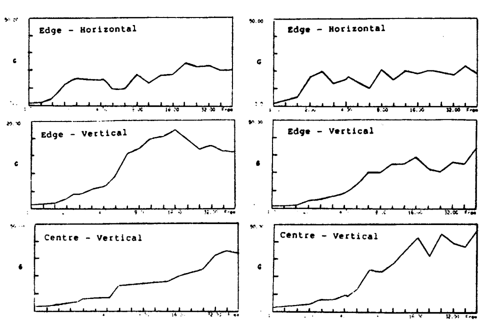

Figure 2 : Typical Test Response Spectra

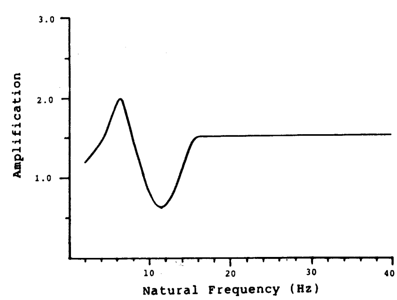

Figure 4 : Typical 'Smoothed' Amplification Spectra