Development of Seismic Force Requirements for Non-structural Components in Taiwan

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ABSTRACT :

Taiwan is located in the circum-Pacific seismic zone. Therefore, the seismic design methods and standards for structures have significantly progressed and been reformed in recent decades. However, earthquake resistant design of equipment and non-structural components is still not popularized in Taiwan.
To investigate the applicability of the seismic design standards to non-structural components, the prescribed requirements for the high-tech equipment according to Taiwan seismic design guideline and SEMI S2 were compared in this paper. In addition, a practical formula was proposed for the seismic design of non-structural components in Taiwan area. The floor response spectra at the target location within an interesting building were developed in order to determine the required seismic design force for the attachments of nonstructural components. Meanwhile, in this paper, the seismic force requirements for several non-structural components specified by Taiwan guideline, NEHRP and IBC were compared for the follow-up research.
On the other hand, NCREE shall take the responsibility to establish an appropriate environment for the increasing requests of non-structural seismic qualification in Taiwan. The input time histories for shaking table test in compliance with the requirements of AC-156 could be generated numerically. The synthetic strong motions which were compatible with the specified response spectrum were simulated by using the phase spectrum of a recorded floor response because it keeps the non-stationary characteristics of an actual response. In addition, the excitations of the shaking table at NCREE and the associated test response spectrum were achieved and discussed in this paper.

KEYWORDS: Non-structural Seismic Force Requirements, floor response spectrum, seismic qualification testing, AC-156, high-tech equipment

1. INTRODUCTION

Seismic design for nonstructural components and equipment is little regarded by architects and structural engineers in Taiwan. There are some reasons resulting in the phenomenon. For example, only the seismic performance of structural components is requested in Building Act, and lots of nonstructural components are installed after the usage building licenses issued. Nowadays there are no particular seismic guidelines for non-structural components in Taiwan, so that *Taiwan Building Code* (TBC) and *Outline Specifications for Public Construction* are applied to the seismic design of mechanical and electrical components. Nevertheless, the anchorage and bracing requirements of Outline Specifications are considered for the functionalities of equipment rather than the seismic demands. Through strong earthquake experiences in recent years, people gradually realize that although the structural damages may not harm the building function, several important facilities and buildings will be forced to be out of operation due to the non-structural problems. In order to meet more and more requirements for improving seismic performance of nonstructural components, there are three parts discussed in this paper. First, the seismic design specification for nonstructural components in Taiwan is compared with NEHRP2003 (FEMA450) and IBC2006 briefly. Then, an equation to calculate the reasonable seismic design force is recommended for the equipment of high-tech industries in Taiwan. Finally, the synthetic time histories for shaking table test were generated numerically in compliance with the requirements specified by AC-156. In addition, the excitations of the shaking table at NCREE and the associated test response spectra would be discussed in this paper briefly.

2. PRESCRIPTIVE SEISMIC DESIGN FORCE REQUIREMENTS

2.1 Background

Previously, seismic force requirements for nonstructural components in Taiwan mostly referred to *Uniform Building Code* (UBC). From 1982 to 2004, the seismic force was calculated by the equation: $F_p=ZIC_pW_p$, where F_p was the seismic design force, Z and I were the seismic zone coefficient and occupancy importance factor, C_p was the component coefficient, and W_p was the component weight. Values of Z and I were the same as for structural design. The value of C_p was 2.0 or 0.75 decided according to the ductile or brittle fracture of components, respectively.

From 2005 to date, referred to IBC 2000, the nonstructural requirements are substantially revised in TBC, and the seismic force is calculated by the following equation:

$$F_{ph} = 0.4 S_{DS} I_p \frac{a_p}{R_{pa}} \cdot (1 + 2h_x / h_n) W_p \tag{2.1}$$

where S_{DS} is the design spectral response acceleration at short periods, I_p is the component importance factor for equipment or components, a_p is component amplification factor, and R_{pa} is allowable component response reduction coefficient. In Eq. (2.1), 0.4 S_{DS} is regarded as the Effective Peak Ground Acceleration (EPA) at the free field, and $0.4S_{DS}(1+2h_x/h_n)$ represents the acceleration at the point of attachment of component with a height h_x respect to the ground level. Furthermore, the values of F_p shall not be taken as less than $0.3S_{DS}I_pW_p$ but needn't be greater than $1.6S_{DS}I_pW_p$.

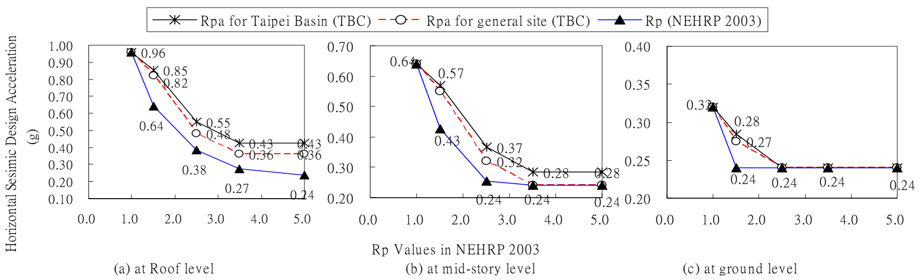

Fig. 1: Influence of different Response reduction coefficients (R_{pa} or R_p) on F_{ph}

There are two main differences in nonstructural requirements between TBC and NEHRP2003. The first one is the vertical seismic force, F_{pv}. In TBC, F_{pv} is defined by $1/2F_{ph}$ for general sites and $2/3F_{ph}$ for near-fault regions, while F_{pv} being defined by $0.2S_{DS}W_p$ in NEHRP2003. The other difference is about the values of component response reduction coefficients, R_p in NEHRP2003 and R_{pa} in TBC. Due to the uncertainties of installation quality and ductility capacity of components and attachments, the values of component response reduction coefficient R_p in TBC are defined within the range of 1.25 to 3.5, while the values being defined between 1.5 and 5.0 in NEHRP2003. Furthermore, in TBC, in order to control the damage level under the design base earthquake, the value of R_p is reduced to the allowable component response reduction coefficient R_{pa} for nonstructural components according to the same specifications for structural system. The effect of R_{pa} or R_p on F_{ph} is shown in Fig. 1, where S_{DS} is defined by 0.8, and a_p and I_p are all equal to 1.0. At roof level, the values of F_{ph} in Taipei Basin are greater than those calculated by NEHRP2003 with a ratio of 1.33 to 1.79, it seems a little conservative to design nonstructural components by TBC. At ground level, most F_{ph} aren't affected by R_{pa} or R_p because F_{ph} with R_p equal or greater than 2.5 are controlled by the lower bond $0.3S_{DS}I_pW_p$.

2.2 Comparison of TBC with NEHRP 2003 and IBC 2006

Recently, nonstructural requirements in the United States change a lot in IBC2006 (ASCE 7-05). To show the differences among TBC, NEHRP 2003 and IBC 2006, the horizontal seismic design forces for nonstructural components at ground or roof level of a regional hospital in Taipei are calculated according to different codes. The components include HVAC, elevator components, electrical components, and piping systems. The results are shown in Fig. 2, where S_{DS} is 0.6, and I_p is equal to 1.5 due to the occupancy factor of regional hospital buildings. Piping system are classified in accordance with ASME B31, high-deformability materials with joints made by welding or brazing, limited-deformability materials with joints made by threading or grooved couplings, and low-deformability materials. It can be observed from Fig. 2:

(1) Design forces for spring-isolated HVAC equipment at both ground and roof level are much larger than other components because of the larger value of a_p for spring-isolated HVAC equipment. In IBC2006, though a_p of vibration isolated components and distribution systems are all equal to 2.5, the associated design acceleration for isolated HVAC equipment is still larger because the lower value of R_p is defined for spring-isolated components.
(2) Except electrical components，the design forces for other components at the roof level determined by TBC are conservative with respect to other codes.
(3) Except spring-isolated HVAC equipment and low-deformability piping, the design forces for other components at the ground level are the same, because they are all controlled by the lower bond $0.3S_{DS}I_pW_p$,. Meanwhile, the design force for spring-isolated HVAC equipment is controlled by the upper bond 1.6 $S_{DS}I_pW_p$.
(4) In IBC 2006, the lower seismic demands can be determined for piping system in accordance with ASME B31 (category 5 and 7 in Fig. 2).

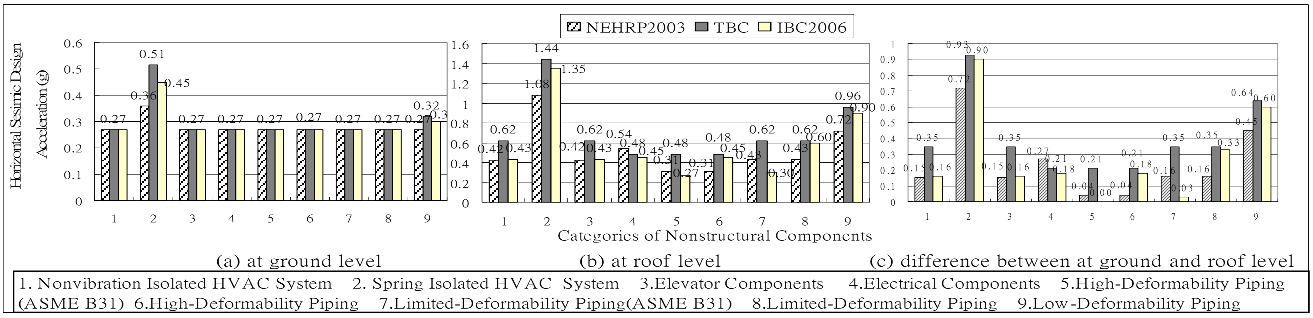

Fig. 2: Comparison of horizontal seismic design acceleration according to different Codes

3. SEISMIC DESIGN FOR EQUIPMENT IN HI-TECH FABS

3.1 Seismic Demand Specified by SEMI S2 and TBC

In addition to TBC for general nonstructural components, some special or important components, like hi-tech equipment, need specific seismic requirements to ensure their seismic performance. For instance, the equipment in production line of semiconductor industry in Taiwan shall comply with SEMI S2, a standard developed by Semiconductor Equipment and Materials International. Based on UBC 1997, the simplified seismic design force specified by SEMI S2 is shown as follows:

$$F_{ph} = C_a(1+3\,h_x/h_n)\frac{a_p}{R_p}I_pW_p = 1.32W_p \tag{3.1}$$

This is based on the assumption that the site is located at seismic zone 4 in United States, with soil profile type S_D and 5 km from a seismic source type A , and the HPM (Hazardous Production Materials) equipment is attached at the mid-story level with shallow anchor bolts. In SEMI S2, because of the high fundamental frequency, the typical semiconductor equipment is assumed as a rigid structure. There are some problems to adopt Eqn. 3.1 for semiconductor industry in Taiwan. First of all, the format is based on UBC 1997, and it is much different from that specified by TBC which is developed on the basis of IBC2000,. Secondly, for a typical hi-tech fab in Taiwan, the production line in cleaning rooms are usually located at the top level of internal structure, which is separated from the outside truss structure. Therefore, equipment shall be assumed to be mounted at the roof level instead of the mid-story level.

In order to determine the most suitable seismic force for semiconductor facilities in Taiwan, two alternative simplified equations are discussed in this section. One is the prescriptive equation based on the format specified by TBC, and the other is modified by real floor response spectrum of hi-tech fabs. Based on the critical assumption that the HPM equipment is mounted by short anchored bolts at the roof level of a hi-tech fab in Tainan Science Park with 2 km from Hsinhua fault, the prescriptive seismic force can be defined as follows:

$$\text{Tainan Science Park:}\quad F_{ph} = 0.4\times0.984\times3\times\frac{1.0}{1.33}\times1.5\times W_p = 1.33W_p \tag{3.2}$$

Compared with Eqn. 3.1, though the original equation and assumptions are not the same, the resulted seismic demands are quite similar. For HPM equipment in Hsin-Chu Science Park with no active fault nearby and smaller S_{DS} than that at Tainan Science Park, the prescriptive seismic force can be also defined as follows:

$$\text{Hsin-Chu Science Park:}\quad F_{ph} = 0.4\times0.7\times3\times\frac{1.0}{1.33}\times1.5\times W_p = 0.95W_p \tag{3.3}$$

3.2 Alternative Equation Based on Normalized Equipment Design Response Spectrum

From Eqn. 3.1 to Eqn. 3.3, we can see the dynamic characteristics of structures of Hi-tech fabs aren’t clearly manifested. To obtain more real interaction between structure and equipment, the amplification factor A_{FP} is proposed in this study on the basis of time history analysis. The time histories of floor response of typical Hi-tech fabs located at Hsin-Chu Science Park corresponding to the spectrum compatible design earthquake (Chai, 2005) are used in this study. Reasonable numerical models were built according to the structural characteristics of the selected fabs, including the equivalent plate element for diaphragm, the RC elements and steel trusses, as well as the mass distributions of heavy equipment (Chai, 2005). The fundamental frequencies for the selected hi-tech fabs in both X- and Y- directions were from 1.9 to 3.3 Hz, which were quite close to those obtained by ambient measurements. In addition, according to the fundamental frequency, the typical

Hi-tech fabs can be taken for short-period structures both in Tainan and Hsin-Chu Science Parks.

As shown in Fig. 3, based on the simulated input ground motions $a_g(t)$ that is consistent with the maximum potential earthquake with a return period of 475 years, the time histories of floor response $R_{es1}(T_s;t)$ at each representative location of the typical Hi-tech fabs can be determined, where T_s is the fundamental period of the selected Hi-tech fabs. Based on each time histories of floor response, the associated normalized floor response spectrum (2%-damping ratio) can be determined while scaling the peak floor response $R_{es1}(T_s;\, t)$ to 1g. Then, the amplification factor A_{FP} can be defined by the normalized floor response spectrum, which is a function of the dimensionless frequency F_p/F_s, where F_p and F_s are the fundamental frequencies of the equipment and the selected Hi-tech fab, respectively. The amplification factors can be determined for the four selected hi-tech fabs in both X- and Y- directions, and the mean and mean+1σ of the eight amplification factors are shown in Fig. 4.

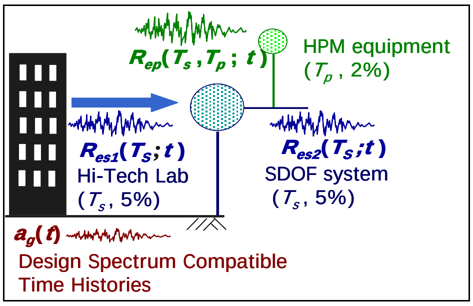

Fig. 3 Procedure of Analysis

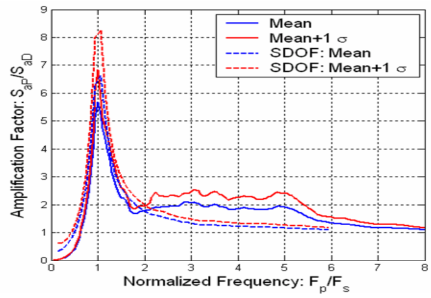

Fig. 4 Comparison of the amplification factor

On the other hand, both the equipment and the supporting structure can be modeled by SDOF systems with fundamental periods of T_p and T_s, and damping ratios of 2% and 5%, respectively. The responses of equipment and the supporting structure are assumed in elastic ranges. Then, based on the same input ground motion as used for the dynamic analysis of multi-degree models, the time histories of the response $R_{es2}(T_s;\, t)$ and the associated spectrum $S_{aD}(T_s)$ of the SDOF structure can be determined . Similarly, based on the time histories of response $R_{es2}(T_s;\, t)$, the associated floor response spectrum $S_{aP}\,(T_s,\, T_p)$ can be determined, and then the amplification factor A_{FP} can be defined by

$$A_{FP} = S_{aP}\,(T_s\,,\, T_p)\,/\,S_{aD}\,(T_s\,) \tag{3.4}$$

Figure 4 shows the mean and mean+1σ of the amplification factors determined under SDOF assumption. It can be found from Fig. 4 that the amplification factor determined by MDOF system can reflect the high mode effect significantly. Based on the amplification factor, the simplified equation to determined seismic design force for attachments of equipment is proposed as follows:

$$F_{ph} = \frac{A_{FP}\, S_{aD}}{R_{pa}}\, I_p\, W_p \tag{3.5}$$

where the value of A_{FP} for flexible equipment is defined by 2.0, and 1.0 for rigid equipment. Herein, a rigid equipment is defined as the associated ratio F_p/F_s is equal to or greater than 8.0, and a flexible equipment is defined as the associated F_p/F_s is between 2.0 and 8.0. Equipment with F_p/F_s smaller than 2.0 has great possibility to be resonant with the supporting structures, and hence is recommended to be analyzed expressly. Generally speaking, a rigid equipment can be defined as its fundamental frequency is higher than 16.6Hz. In this case, the frequency of a rigid equipment may be greater than 16.0 Hz since F_s of the selected typical Hi-tech fabs are larger than 2.0 Hz. The comparison of amplification factor and the normalized equipment response spectrum according to different studies is shown as Fig. 5, which is under the assumption that the equipment is mounted at roof level, and the supporting building is classified as a short-period structure. From Figs. 4 and 5, we can see that using design spectra as adopted by previous studies may underestimate the effect of higher modes of Hi-tech fabs.

Following the same conditions in section 3.2, the design force for HPM equipment is calculated by Eqn. 3.6:

$$\text{Tainan Science Park:} \quad F_{ph} = \frac{1.0 \times 0.984}{1.33} \times 1.5 \times W_p = 1.11 W_p \tag{3.6a}$$

$$\text{Hsin-Chu Science Park:} \quad F_{ph} = \frac{1.0 \times 0.7}{1.33} \times 1.5 \times W_p = 0.79 W_p \tag{3.6b}$$

where S_{aD} is equal to S_{DS} because the selected fabs are recognized as short-period structures at both Tainan and Hsin-Chu Science Park, and HPM equipment is still regard as a rigid component. Comparing to Eqn. 3.2 and 3.3, the seismic demand based on Eqn. 3.8 is reduced to 83%. But for flexible equipment with F_p/F_s<8.0, the seismic demands would be amplified by 1.66 times.

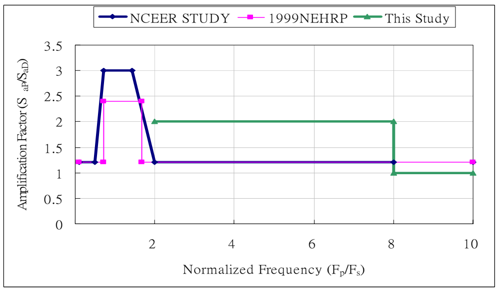

Fig. 5: Comparison of normalized equipment response spectrum according to different studies

4. SEISMIC QUALIFICATION TESTING OF NONSTRUCTURAL COMPONENTS

AC156, issued by ICC Evaluation Service, Inc., is one of the seismic qualification testing guidelines for general types of nonstructural components that are approved by IBC 2006 and ASCE 7-05. The current edition of AC156 (2007) is applicable to nonstructural components and systems with fundamental frequencies greater than or equal to 1.3 Hz. Either triaxial, biaxial or uniaxial testing can be performed in compliance with the specified requirements. Other testing guidelines used for nonstructural components include GR-63-CORE and IEEE 344, which are developed for telecommunication equipment and Class 1E equipment in nuclear power generating stations, respectively. Fig. 6 shows the comparison of three nonstructural seismic qualification guidelines.

In accordance with AC156 and GR-63-CORE, the associated RRSs (Required Response Spectrum) for the region with highest S_{DS} value (S_{DS}=1.136 g) in Taiwan are compared in Fig. 7. The shape of the RRS corresponding to GR-63-CORE almost envelopes the one in compliance with AC156, and the ratio is up to 2.75 in the range of 2~5 Hz for the horizontal directions. In addition, the RRS specified for vertical direction in GR-63-CORE is much larger than that specified in AC156 because GR-63-CORE adopts the same RRS for both vertical and horizontal directions. Furthermore, compared with other equipment, the weight of telecommunication equipment is relatively low, and hence, it should be noted that the tested equipment with heavy weight may be damaged owing to the extremely inertial load during the qualification testing in compliance with the requirements of GR-63-CORE.

		AC 156	GR-63-CORE (Zone 4)	IEEE-344
Resonant Frequency Search Test				
	Amplitude of Sweep	0.1g±0.05g	0.2g	0.2g
	Frequency Range	1.3~33.3Hz	1~50Hz	1~33Hz
	Sweep Rate	2 Oct. /1 min.	1 Oct. /1 min.	equal or less than 2 Oct. /1 min.
Multifrequency Seismic Simulation Test				
RRS	Damping Ratio	5%	2%	5%
	Frequency Range	1.3Hz~33.3Hz	1.0Hz~50.0Hz	1.0Hz~33.0Hz
	Amplified Rigion	1.3~8.3Hz	2~5Hz	-
	A_{flex} (Roof floor)	1.6S_{DS}	5.0g	-
	A_{rig} (Roof Floor)	1.2S_{DS}	1.6g	-
	RRS of Vertical direction	A_{flex}=2/3 S_{DS} A_{rig}=2/3(0.4S_{DS})	same as horizontal direction	-
TRS	Damping Ratio	5%	2%	equal or larger than 5%
	Tolerance upper limit	130%	130% (1~7Hz)	-
	Tolerance lower limit	90% (conditional)	100%	90% (conditional)
Input Motion	Peak Acceleration	equal or larger than ZPA value of RRS	-	equal or larger than ZPA value of RRS
	Total Duration	30 sec., at least 20 sec. of strong motion	the designated motion is about 30 sec.	at least 15 sec. of strong motion

Fig. 6 Requirements for seismic qualification testing in AC156, GR-63-CORE and IEEE-344

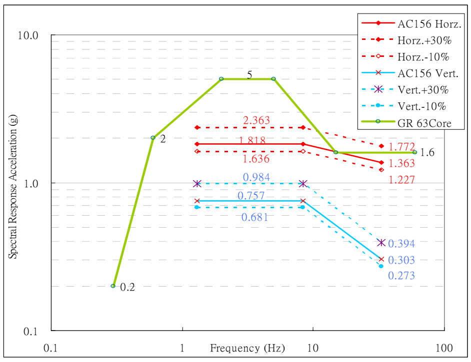

Fig. 7 RRS of AC156 and GR-63-CORE

Based on the incorporation with NCREE laboratory in proceeding some seismic qualification shaking table tests of nonstructural components, the applicability of AC156 can be further understood. The synthetic input motions for shaking-table tests can be generated on the basis of the phase spectrum of an observed ground motions and the modified Fourier amplitude, such that the associated response spectrum is compatible with the RRS specified by AC156. Based on the phase spectrum and a trial Fourier amplitude $A_m(\omega)$, the time histories of excitation can be recovered and then the associated spectral response acceleration $S_{am}(T_p)$ for any nonstructural period T_p can be determined. Because the response will be dominated by the excitation with resonant frequency, the modification factor for the Fourier amplitude at a circular frequency of $\omega = 2\pi/T_p$ can be defined by

$$MF_m(\omega)\big|_{\omega=2\pi/T_p} = S_{aP}(T_p)/S_{am}(T_p) \tag{4.1}$$

where $S_{aP}(T_P)$ is the spectral acceleration demand at period T_p according to RRS. Then, the Fourier amplitude $A_{m+1}(\omega)$ on the next iteration can be defined by

$$A_{m+1}(\omega) = MF_m(\omega) \times A_m(\omega) \tag{4.2}$$

This iteration process will be continued until $MF_m(\omega)$ is equal to 1.0 at all frequencies, and hence the final recovered excitation will be compatible with the RRS. Figure 9 shows the synthetic input motions that are generated by keeping the phase spectra of Chi-Chi earthquake recorded in CHY009 and TCU054 stations, and it can be observed that the associated horizontal and vertical response spectra are compatible with the RRS well.

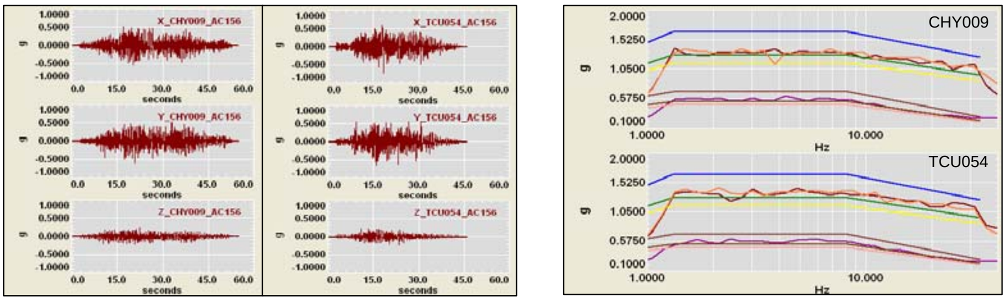

Fig. 9 Synthetic time histories and response spectra compatible with AC-156 RRS

For the testing in compliance with AC156, in order to study the influence of heavy weight on TRS (test response spectrum), a set of lead blocks with 28 tons was used first in the pilot test to model the tested equipment with a weight of 30 tons. In contrast to the case without any specimen, it can be found that the TRS in x-direction is affected significantly by the heavy weight of specimen. As shown in Fig. 10, the measured TRS corresponding to heavy specimen exceeds the tolerance (30% of RRS) over the range of 1~5Hz and 15~20Hz, and the results may be caused by table and specimen weight, resonance problem, force feedback, and stability of table performance. The most effective solution to this problem is to carry out a model measurement test with specimen attached to the table before executing the formal qualification test. The model test can incorporate the compensation in a time history test to remove the dynamic effects of the control system by adjusting the drive signal. However, it needs to be considered that the specimen may be damaged during the model test due to the large amplitude (usually 350 gal) and long durations (approximately 6 minutes).

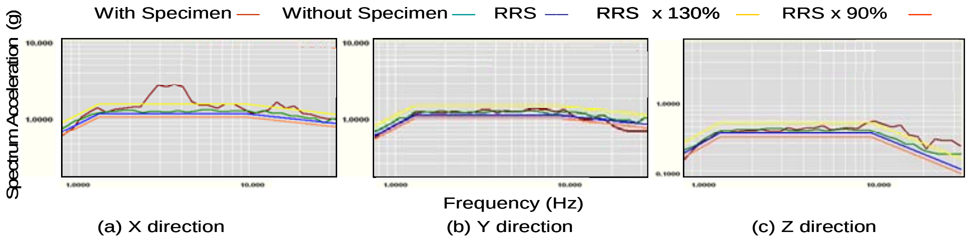

Fig. 10 TRS and RRS in the testing for AC156

5. CONCLUSIONS

In the first part of this paper, seismic requirements in TBC, IBC 2006 and NEHRP2003 are compared briefly. In the second part, the equation used to determine the reasonable seismic design force based on normalized floor response spectrum is recommended for the equipment of hi-tech industries in Taiwan. In the third part, the testing guidelines used for seismic qualification of nonstructural components are compared and the synthetic time histories which are compatible with the RRS specified by AC-156 were generated. Potential problems of execution of shaking table tests for seismic qualification are addressed as well.

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