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SEISMIC CERTIFICATION OF UNANCHORED COMPONENTS: RELIABILITY ASSESSMENT OF THE ICC-ES AC156 PROTOCOL

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Abstract: *The paper presents the preliminary results of a study on the seismic certification of unanchored acceleration-sensitive components by means of shake table testing. The application of the ICC-ES AC156 protocol for seismic assessment of unanchored blocks is preliminarily reviewed. Numerical rigid block analysis of several component geometries is performed considering (a) a wide reference set of real records (ATC63), and (b) artificial inputs generated according to the AC156 protocol. The fragility curves of the components are evaluated considering several damage states, and reliable dimensionless intensity measures. The ATC63 results are compared to the AC156 protocol ones checking whether the protocol records are representative of realistically severe earthquake scenarios. The reliability index related to the protocol is assessed according to the first-order reliability method. The real accelerogram results are considered as a capacity measure, and the protocol ones as demand measure. The criticalities of the AC156 protocol are finally evidenced as well as guidelines for a safe application of the protocol are provided.*

Introduction

Nonstructural components and building contents often represent the most significant part of the initial and maintenance costs of public and critical facilities (Taghavi and Miranda, 2003). For critical facilities such as hospital buildings, the seismic response of such components is likely to be a direct or indirect cause of human losses, e.g., crush injury or escape way obstruction (Cosenza et al., 2015; Mitrani-Reiser et al., 2012; Nikfar and Konstantinidis, 2019). Conversely, such buildings should remain in service in case of low-to-moderate intensity earthquake events.

The stability and the functioning of nonstructural components and building contents are to be guaranteed for (a) all components of critical facilities, and (b) life-safety systems of all buildings (American Society of Civil Engineers, 2010). Nonstructural components are often classified in acceleration- and displacement-sensitive components. The classification is essentially based on the engineering demand parameter better correlated to the performance levels of the components (Petrone et al., 2015), or more generally, on the nature of the dynamic response of the components and their boundary conditions. Damage of acceleration- (displacement-) sensitive components is essentially due to inertial effects (excessive relative displacement between the structural attachments). The classification is exemplifying and not complete, and mixed response is often observed in real case applications (Magliulo et al., 2014).

An extremely significant effort has been recently made by the researchers in order to assess the seismic performance of critical acceleration-sensitive components (Di Sarno et al., 2019; Filiatrault and Sullivan, 2014; Konstantinidis and Makris, 2009; Nikfar and Konstantinidis, 2019; Wittich and Hutchinson, 2015). Shake table testing represents the most referenced method for seismic assessment of acceleration-sensitive components, and several National and International codes define testing protocols and guidelines (Federal Emergency Management Agency (FEMA), 2007; Institute of Electrical and Electronics Engineers (IEEE), 2013; International Code Council Evaluation Service (ICC-ES), 2012; Telcordia Ericsson, 2017; Wittich and Hutchinson, 2014); some of them are also meant as certification/qualification protocols (Institute of Electrical and Electronics Engineers (IEEE), 2013; International Code Council Evaluation Service (ICC-ES), 2012).

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Unattached elements are among the most critical nonstructural components (Mitrani-Reiser et al., 2012; Nikfar and Konstantinidis, 2019). This is due to several reasons: (a) complexity of component dynamic response (e.g., rocking-dominated), (b) wide and severe dynamic motion (large displacements/rotations), and (c) potential location in critical and public facilities (e.g., hospital equipment) (Di Sarno et al., 2019; Mitrani-Reiser et al., 2012). The seismic risk related to such components can be extremely high. The methods and the procedures for their performance assessment are not clearly addressed by the regulations, and as things stand, there is no existing protocol conceived for seismic certification of unanchored components. The most used protocols (e.g., AC156 (Federal Emergency Management Agency (FEMA), 2007; International Code Council Evaluation Service (ICC-ES), 2012)) are conceived for attached elements, and their reliability with regard to freestanding components is not known *a priori* (Di Sarno et al., 2019). Despite that, there is a growing literature based on the extension of testing protocols not specifically aimed to freestanding components to such type of components (Burningham et al., 2007; Cosenza et al., 2015; Di Sarno et al., 2019; Mahdi and Mahdi, 2013)

The paper presents the results of an extensive numerical analysis aimed to assess the reliability of the AC156 protocol (International Code Council Evaluation Service (ICC-ES), 2012) as a shake table testing certification means for unattached components. The study follows up the preliminary findings presented in (D'Angela et al., 2019). The seismic performance of blocks having several geometries is evaluated considering both real accelerograms (ATC63 (Applied Technology Council (ATC), 2008)), and AC156 inputs. The reliability index of the protocol is evaluated comparing the real accelerogram and the AC156 results according to the first-order reliability method (FORM) (Schultz et al., 2010), i.e., considering the former as a capacity measure, and the latter as a demand measure.

Seismic certification of nonstructural components

Regulations and practice: the available protocols

The seismic certification of nonstructural components, sometimes referred as seismic qualification, is a standard approval certification stating that the seismic performance of the considered nonstructural components (or building contents) has been assessed, and it meets the applicable functional requirements. The special seismic certification (SSC), also known as seismic qualification of equipment and components (International Code Council, 2018, sec. 1708.5) and seismic certification for designated seismic systems (American Society of Civil Engineers, 2010, sec. 13.2.2), represents the state-of-art of the nonstructural component certification. SCC is required for peculiar categories of designated seismic systems (i.e., component/system having importance factor I_p larger than 1.0) in case of seismic design categories C through F (American Society of Civil Engineers, 2010, sec. 13.2.2; Federal Emergency Management Agency (FEMA), 2009). In particular, it refers to (a) active mechanical/electrical equipment required to remain in service in case of (design) earthquake occurring, (b1) components containing hazardous/toxic substances, and (b2) components having I_p equal to 1.5 (American Society of Civil Engineers, 2010, sec. 13.1.3). Essentially, this latter condition is applicable to (a) most equipment and contents of critical facilities such as hospital buildings, and (b) life-safety systems included in all building systems and facilities (e.g., fire protection systems). The certification can be performed by (a) shake table testing (American Society of Civil Engineers, 2010, sec. 13.2.5), (b) experience data analysis (American Society of Civil Engineers, 2010, sec. 13.2.6), and (c) (numerical) analysis, except for mechanical/electrical equipment that cannot be certified by analysis (shake table is preferred). The AC156 code (International Code Council Evaluation Service (ICC-ES), 2012) is the reference protocol for component certification through shake table testing (American Society of Civil Engineers, 2010, sec. 13.2.6). The equipment supplier should provide the certification according to the technical opinion of the registered design professional in charge, which is responsible for the evidence review.

The California OSHPD (Office of Statewide Health Planning and Development (OSHPD), 2007) defines the framework for the seismic certification of nonstructural components, especially for equipment hospital facilities. The OSHPD code application notices (CANs) explicitly interpret the specific sections of the regulations (American Society of Civil Engineers, 2010; California Building Standards Commission, 2016) fully addressing the certification of nonstructural components (Office of Statewide Health Planning and Development (OSHPD), 2007, no. CAN 2-1708A.5). The OSHPD manages, reviews and approves the SSC procedures. OSHPD refers to AC156 protocol, specifying that only laboratories having ISO Accreditation Standard 17025 are allowed to perform shake table testing for certification purposes.

Some other protocols are defined for more specific components such as electric and electronic equipment. The Institute of Electrical and Electronics Engineers (IEEE) supplies protocols and guidelines for the seismic qualification of equipment of nuclear power generating stations (Institute of Electrical and Electronics Engineers (IEEE), 2013). Telecommunication industry defines certification protocols for telecommunication network equipment (Telcordia Ericsson, 2017). A reference shake table protocol for (acceleration-sensitive) nonstructural components is also provided by (Federal Emergency Management Agency (FEMA), 2007). FEMA461 was developed by the US Applied Technology Council (ATC), the Mid America Earthquake Engineering Research Center (MAE Center), the Multidisciplinary Center for Earthquake Engineering Research (MCEER), and the Pacific Earthquake Engineering Research Center (PEER), with funding from the Federal Emergency Management Agency and the National Science Foundation. FEMA461 shake table protocol is finalized to the evaluation of the seismic performance of the components (e.g., fragility assessment), and not explicitly to the certification. However, the protocol may be used for that purposes with due consideration (Burningham et al., 2007; Mosqueda et al., 2009).

ICC-ES AC156 protocol

The AC156 protocol, namely *Acceptance Criteria for the Seismic Certification of Nonstructural Components*, was developed by the International Code Council Evaluation Service (ICC-ES). It is the reference code for International Building Code (IBC) (International Code Council, 2018), ASCE/SEI 7-10 (American Society of Civil Engineers, 2010), and OSHPD (Office of Statewide Health Planning and Development (OSHPD), 2007). The protocol is conceived for (common) acceleration-sensitive components such as ceiling systems and base anchored elements (Mosqueda et al., 2009; Wittich and Hutchinson, 2014). AC156 protocol is certainly the most used protocol for research and practice applications (Burningham et al., 2007; Chai and Lin, 2011; Di Sarno et al., 2019). This can be used if the component to be tested has fundamental elastic frequencies larger than 1.3 Hz. The shake table loading history should be a non-stationary broadband random excitation signal with at least 20 s of strong motion (often 30 s total duration), and having frequency contents ranging in 1.3 – 33.3 Hz. The test response spectrum (TRS) should match the required response spectrum (RRS). A reference RRS is provided by the code, but this can also be evaluated through analysis of structural response. The spectral response acceleration at short periods s_{DS} should be considered as an intensity parameter. Figure 1 shows both horizontal and vertical RRS provided by (International Code Council Evaluation Service (ICC-ES), 2012).

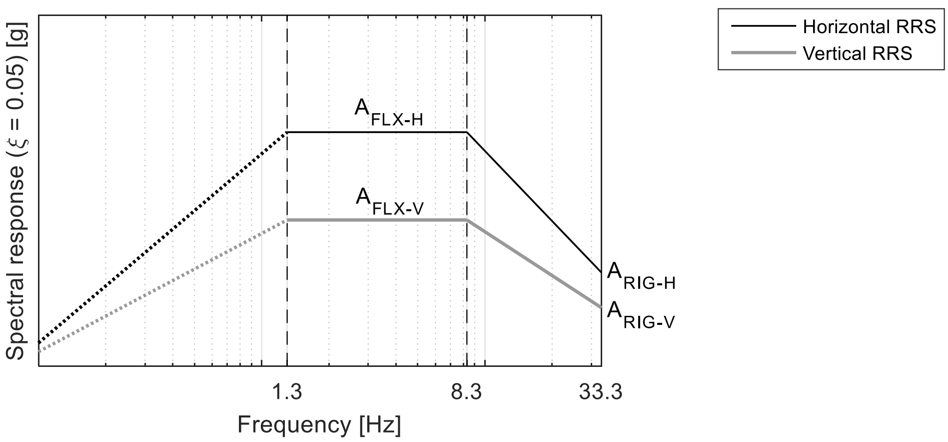

Figure 1. AC156 Required Response Spectra (RRS) (International Code Council Evaluation Service (ICC-ES), 2012).

The plateau and rigid period spectral accelerations of the RRS (A_{FLX-H}, A_{RIG-H}, A_{FLX-V}, and A_{RIG-V}) are defined as a function of both s_{DS} and component height factor ratio *z/h* (*z* is the height of the component attachment point, and *h* is the building roof height). The maximum amplification of the horizontal RRS (i.e., A_{FLX}/A_{RIG}) results equal to 2.5, except for cases in which $A_{FLX,H}$ exceeds 1.6

s_{DS} (occurring for $z/h > 0.3$), where the ratio (logarithmically) decreases along with z/h up to a value equal to 1.33 for $z/h = 1$. Several spectral compatibility limitations should be checked according to strict conditions. The inferior frequency limit for the RRS spectral compatibility can be larger than 1.3 Hz if (a) there is evidence of no component resonance below 5 Hz (limit equal to 3.5 Hz), and (b) there is evidence of resonance below 5 Hz (limit equal to 75% of the lowest resonant frequency). Upper and lower bound spectral limits are defined for the TRS as a function of the RRS ordinate (130% and 90%, respectively), even considering exceptions. Among the limitations, the peak table acceleration is required to be larger or equal to the 90% of A_{RIG} value.

Unanchored components, rigid motion and low frequencies

Unanchored components are often meant as rigid blocks (Petrone et al., 2017) essentially for (a) their relative stiffness, and (b) the peculiar nature of their boundary conditions. Rigid block motion has been extensively studied since early times (Housner, 1963; Yim et al., 1980), and several numerical models have been developed (Makris and Konstantinidis, 2003; Petrone et al., 2017; Purvance et al., 2008). The main parameters governing the rigid motion of blocks are shown in Figure 2, and reported in Equations 1, where: R is the block diagonal semi-dimension, θ is the rigid block rotation, α is the critical rigid block rotation, and p is the frequency parameter. The rigid motion equation is reported in Equation 2 (Housner, 1963).

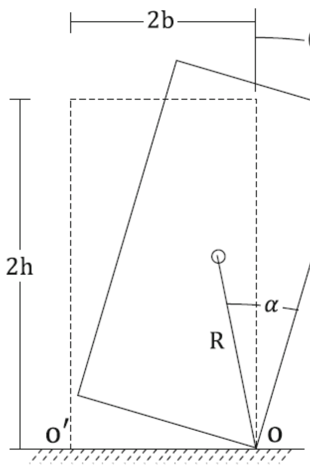

Figure 2. Rigid block geometry.

$$\alpha = \tan^{-1}\left(\frac{b}{h}\right);\ p = \sqrt{\frac{3g}{4R}};\quad R = \sqrt{b^2 + h^2} \tag{1}$$

$$\ddot{\theta}(t) = -p^2\left\{\sin\left[\alpha\ \mathrm{sgn}(\theta(t)) - \theta(t)\right] + \frac{\ddot{u}_g(t)}{g}\cos\left[\alpha\ \mathrm{sgn}(\theta(t)) - \theta(t)\right]\right\} \tag{2}$$

The block response under free rocking motion can be defined by the *rocking period* (or *rocking duration*) T_r, i.e., twice the time in between consecutive zero crossings in the rocking angle trace. T_r can be defined as a function of (a) semi-diagonal block dimension R, and (b) initial rigid block rotation θ_0 to critical rigid block rotation α ratio (Equation 1, where g is the gravity acceleration constant) (Housner, 1963; Wittich and Hutchinson, 2014).

$$T_r = 4\left(\frac{3g}{4R}\right)^{-0.5} \mathrm{acosh}\left[\left(1 - \frac{\theta_0}{\alpha}\right)^{-1}\right] \tag{3}$$

Figure 3 shows rocking frequency f_r (i.e., T_r^{-1}) for a wide range of R. Under loading histories other than sinusoidal inputs, the rocking motion of rigid blocks can be extremely complex, and the component resonant frequencies are not only depending on the geometry of the block. The frequencies to which the motion is more sensitive range between (a) the sinusoidal rocking frequencies and (b) the natural vibration frequencies evaluated at low intensities (i.e., when no significant rocking motion is observed (Di Sarno et al., 2019, 2015)). These latter frequencies are likely to be significantly larger than the rocking ones in case of relatively stiff components (Di Sarno et al., 2019). The more the block motion is severe and rocking-dominated, the more the actual component resonance frequencies are expected to be closer to the (sinusoidal) rocking frequencies (Equation 2).

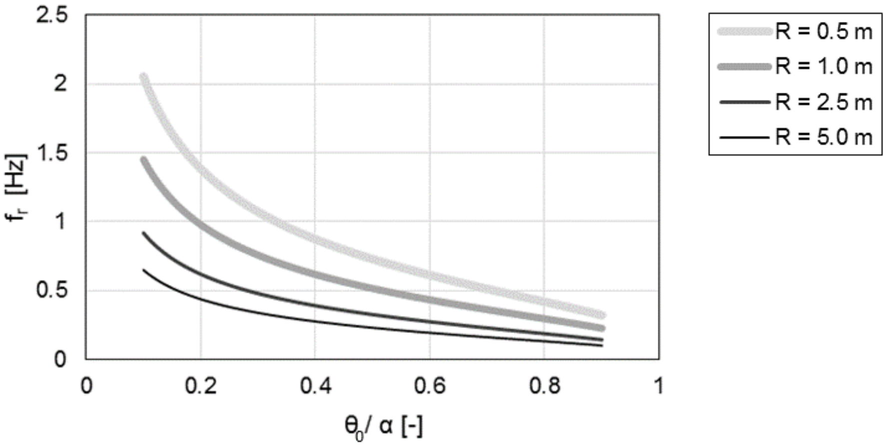

Figure 3. Rocking frequency (f_r) as a function of initial rigid block rotation (θ_0) to critical rigid block rotation (α) ratio (Housner, 1963; Wittich and Hutchinson, 2014).

Relatively stiff freestanding/unanchored components such as hospital equipment are expected to exhibit a rocking-dominated motion under earthquake shakings (Di Sarno et al., 2019; Konstantinidis and Makris, 2009); their seismic performance is expected to be particularly sensitive to the lower frequencies. The rocking frequency is likely to result lower than 1.3 Hz for relatively large blocks, e.g., R > 1.0 m (Equation 1 and Figure 3). This frequency value represents the inferior limit for the spectral compatibility of the AC156 protocol. Therefore, the seismic inputs compatible with the AC156 RRS are likely to be lacking in the frequency range more affecting the vulnerability of the unanchored blocks. Moreover, the application of the AC156 protocol to unattached components is not clearly claimed, and the main applicability condition of the protocol, i.e., resonant component frequency not smaller than 1.3 Hz, is not univocally applicable for unattached elements.

Numerical analysis of rigid blocks

Numerical analysis of bi-dimensional rigid blocks is performed solving the rigid block motion equations (Housner, 1963) by means of the Runge-Kutta ordinary differential equation solver (The MathWorks Inc., 2018). The restitution coefficient is assumed as unitary, according to (Petrone et al., 2017). The analysis approach has already been validated in (Di Sarno et al., 2019) with reference to the extensive parametric study performed in (Petrone et al., 2017).

Two sets of five block geometries are considered; the Set 1 was derived by the geometry of a typical single-window hospital cabinet (Cosenza et al., 2015), and the Set 2 was derived by a large block representative of monumental blocks (Yim et al., 1980). The considered geometries are reported in Table 1.

Dimension		**Set 1**					**Set 2**				
R (→)	[m]	0.36	0.72	**0.72**	0.72	1.43	1.52	3.05	**3.05**	3.05	4.57
h/b	[-]	3.92	1.96	**3.92**	7.83	3.92	5.00	2.50	**5.00**	7.50	5.00

Table 1. Geometries of the analysed blocks (The dimensions in bold are related to the reference block dimensions of the sets).

Two sets of accelerograms are considered for the analysis: real accelerograms ATC63 (Applied Technology Council (ATC), 2008), and AC156 protocol inputs (International Code Council

Evaluation Service (ICC-ES), 2012). Set a includes (44) far fault and (28) near-fault with pulse records provided by ATC63 (Applied Technology Council (ATC), 2008). Seven artificial records were generated according to the AC156 protocol, considering the procedure developed in (Magliulo et al., 2013), adopted in several other studies (Di Sarno et al., 2019). The statistical response spectra of both accelerogram sets are shown in Figure 4 (PFA equal to 1.0 g). It is worth noting that the real accelerogram spectral ordinates are overall larger than the AC156 input ones for low frequencies (e.g., lower than 0.9 Hz), and for the amplified region (e.g., 1.4 to 10 Hz).

Incremental Dynamic Analysis is performed considering both Set 1 and Set 2 geometries, and both Set a and Set b records. The PFA (rigid block rotation θ) is selected as intensity (damage) measure. The analyses are performed with a constant intensity increment equal to 10% of the initial increment PFA; this latter increment was set equal to 0.8 *g b/h*. The analyses are performed until the rigid block rotation θ exceeded (for the first time) the critical value α (Equation 2).

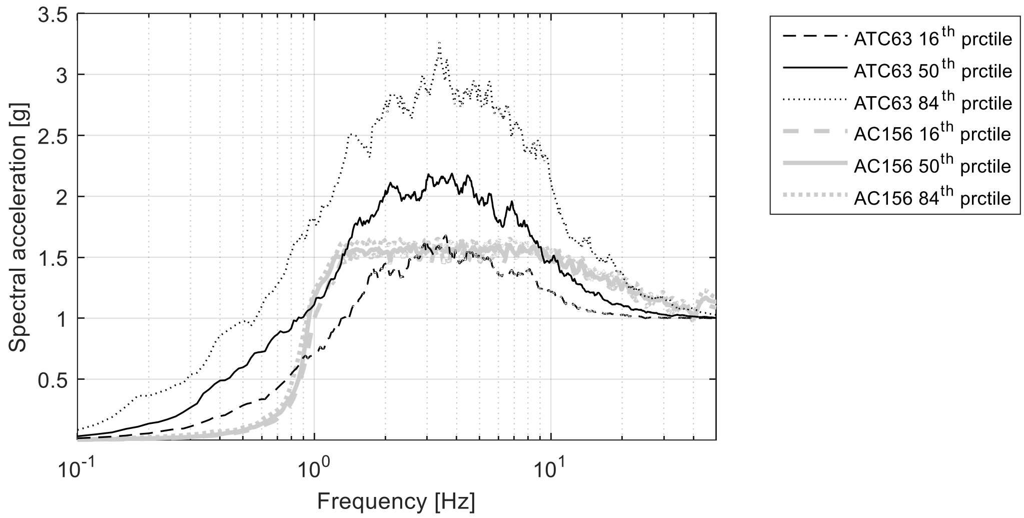

Figure 4. Statistical response spectra related to both ATC63 and AC156 records. All inputs have PFA equal to 1.0 g.

Fragility and reliability index

The fragility curves of the blocks have been evaluated using *Porter method A* (Porter et al., 2007). Typically, only conventional (incipient) rocking ($\theta_{max}/\alpha \geq \sim 0$) and overturning ($\theta_{max}/\alpha \geq 1$) are considered as damage states (Di Sarno et al., 2019; Petrone et al., 2017). A number of 12 damage states is considered in this study, i.e., assuming $\theta_{max}/\alpha \geq$ {0.01, 0.05, 0.1, 0.2, 0.3. 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0}. This is finalised to also investigate the rocking response in between the incipient rocking and the overturning. IM_4 (*PFA*/(*g.tanα*)) and IM_5 (p.*PFV*/(*g.tanα*)) are considered for both Set 1 and Set 2. Such dimensionless intensity measures were developed in (Dimitrakopoulos and Paraskeva, 2015), and their reliability as rigid block response descriptors was assessed in (Petrone et al., 2017). The median values of the fragility curves are plotted as a function of θ_{max}/α in Figure 5 for (a) Set 1 and IM_4, (b) Set 2 and IM_4, (c) Set 1 and IM_5, and (d) Set 2 and IM_5. The ATC63 results (72 real records) are meant as *actual capacities* of the blocks.

AC156 inputs overall produce an overestimated capacity of the blocks if IM_4 is considered as an intensity measure (Figure 5.a and b). This is extremely significant for larger blocks (Figure 5.b). If IM_5 is considered, AC156 results underestimate the capacity for small blocks, and for the incipient rocking of large blocks. The cases having R about 1.5 m (i.e., Figure 5.a.5 and Figure 5.b.1 for IM_4, and Figure 5.c.5 and Figure 5.d.1 for IM_5) represent a limit condition between the small (e.g., R < 1.5 m) and large block (e.g., R > 1.5 m) response.

The reliability of the AC156 protocol is evaluated according to the first-order reliability method (FORM) (Schultz et al., 2010), typically used for the assessment of the structural safety. Since AC156 results are meant as nominal capacities, and the ATC63 as actual capacities, the former can be assumed as *demand measures* (*S*), and the latter as *capacity measures* (*R*). The margin *Z* between *R* and *S* essentially represents the *overcapacity* of the components virtually designed according to the AC156 results. A log-normal probability distribution is assumed for uncorrelated *S* and *R* as an analogy with the fragility evaluation. The reliability index β is calculated using the

Equation 4 (Schultz et al., 2010), where m_R and m_S (V_R and V_S) are the medians (*coefficients of variation*, i.e., standard deviation-to-mean ratio) of *R* and *S*, respectively. The index β can be geometrically defined as the probability distance between the margin mean value and the margin point of failure (Z = 0), normalised considering the margin standard deviation.

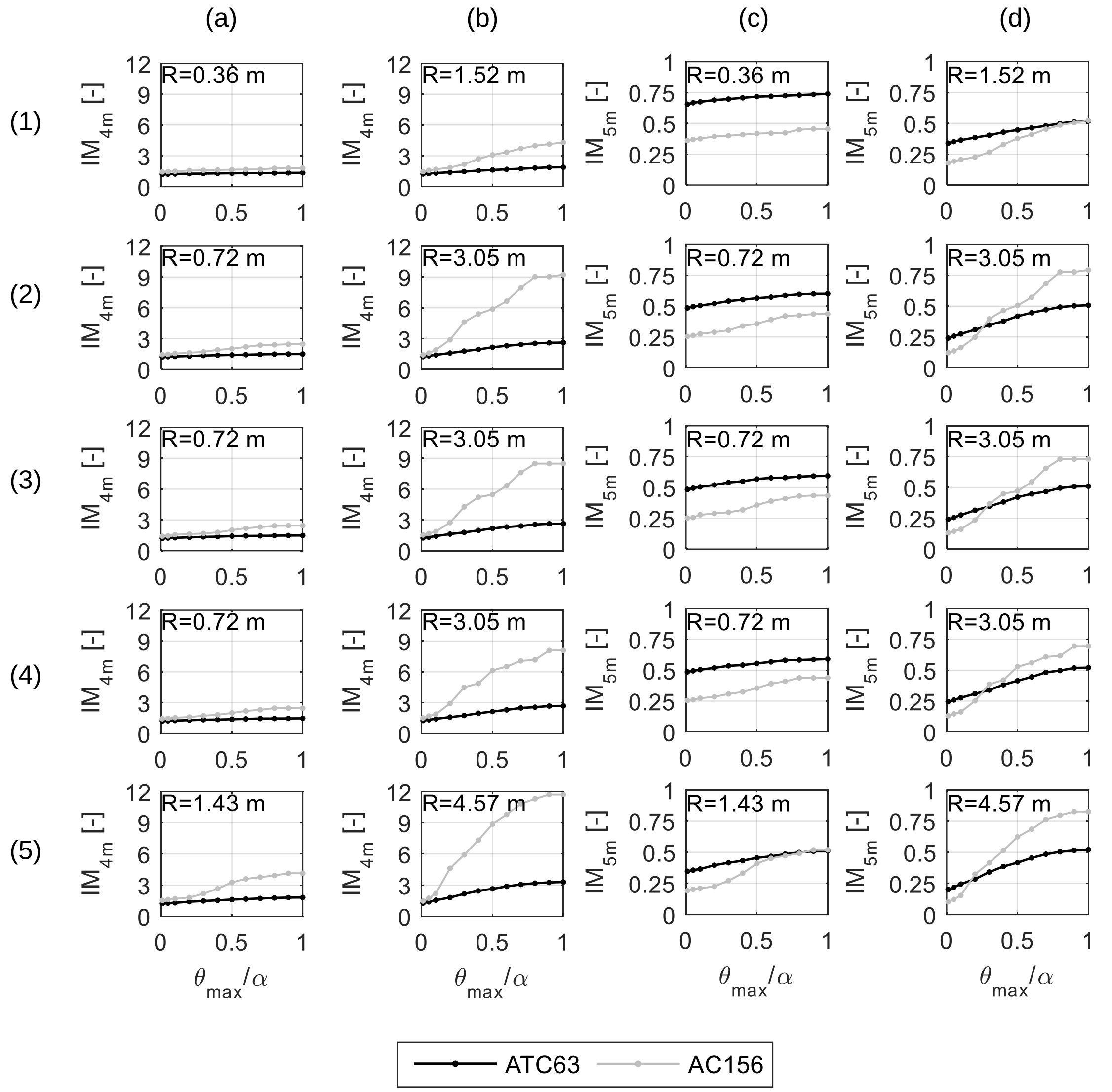

Figure 5. Fragility median values as a function θ_{max}/α of for (a) Set 1 and IM_4, (b) Set 2 and IM_4, (c) Set 1 and IM_5, and (d) Set 2 and IM_5. The component geometry cases (1-5) are ordered according to Table 1 (increasing R).

$$\beta = \frac{\ln\left(\frac{m_R}{m_S}\right)}{\sqrt{\ln(1+V_R^2)+\ln(1+V_S^2)}} \tag{4}$$

Table 2 reports the reliability index β calculated considering both IM_4 and IM_5 for incipient rocking ($\theta_{max}/\alpha \geq 0.01$) and overturning ($\theta_{max}/\alpha \geq 1$). As already observed in Figure 5, AC156 capacities evaluated considering IM_5 are more reliable than the ones calculated using IM_4. The reliability index related to IM_4 (IM_5) is negative in all cases (for the overturning of large blocks). The probability of failure p_f (i.e., probability that the margin Z is lower or equal to zero) is defined as $\Phi(-\beta)$, where Φ is the standard normal function (Schultz et al., 2010). When β is negative, p_f is larger than 50 %, and a value of β ranging in 0 – 1 produces a value of p_f included within 50 % (i.e., $\Phi(0)$) and ~ 16 % (i.e., $\Phi(-1)$).

Given the relatively large number of considered records (i.e., equal to 7 for AC156, and equal to 72 for ATC63), the mean/median value could be used as a reference. Furthermore, since *Z* is an overcapacity in addition to the potential design safety factor, an optimum β would range in 0 – 1 (p_f within 50 ~ 16 %), and a larger value could be considered as conservative. Therefore, AC156 protocol is proven to be unreliable if IM_4 (and equivalently PFA) is considered, for both rocking and overturning (for any dimension of the blocks). If IM_5 is considered, the protocol is conservative for rocking prediction (for any dimension of the blocks), and reliable (slightly unsafe) for overturning prediction of small-to-medium (medium-to-large) block dimensions.

In the light of the fragility and reliability results, the seismic certification of unanchored acceleration-sensitive components should be performed considering IM_5 (and equivalently PFV for given geometries) as an intensity measure. In particular, for rocking assessment, the protocol would be conservative, and for overturning assessment, an additional safety factor should be applied for medium-to-large blocks (e.g., R > 1.5 m). Conversely, IM_4 (and equivalently PFA for given geometries) should not be considered since the capacity of the components would be significantly overestimated.

Geometry and Reliability index		**Set 1**					**Set 2**				
R (→)	[m]	0.36	0.72	0.72	0.72	1.43	1.52	3.05	3.05	3.05	4.57
h/b	[-]	3.92	1.96	3.92	7.83	3.92	5.00	2.50	5.00	7.50	5.00
β_r | IM_4	[-]	-1.80	-1.21	-1.09	-1.51	-1.84	-1.25	-0.94	-1.74	-1.31	-0.95
β_r | IM_5	[-]	**1.19**	**1.42**	**1.41**	**1.36**	**1.27**	**1.39**	**1.48**	**1.30**	**1.37**	**1.43**
β_o | IM_4	[-]	-1.83	-2.33	-1.55	-2.02	-1.75	-2.35	-2.18	-1.70	-2.01	-2.31
β_o | IM_5	[-]	**0.94**	**0.71**	**0.67**	**0.66**	**-0.03**	**-0.03**	**-1.01**	**-0.82**	**-0.65**	**-0.95**

Table 2. Reliability index β calculated for incipient rocking (β_r, $\theta_{max}/\alpha \geq 0.01$), and overturning ($\beta_o$, $\theta_{max}/\alpha \geq 1$), and both IM_4 and IM_5.

Conclusions

The study investigates the seismic certification of unanchored acceleration-sensitive component using shake table testing. Incremental dynamic analysis of rigid blocks is performed considering both real accelerograms (ATC63) and artificial records derived by the AC156 protocol. This latter code is the most used protocol for the certification of acceleration-sensitive components. Several geometry dimensions are considered, ranging from small components, representative of hospital cabinets or bookshelves, to large blocks representative of monuments or museum objects. Fragility curves are estimated using *Porter method A* considering several damage conditions and both dimensionless peak acceleration and peak velocity. The protocol fragilities are compared to the real record ones. The reliability of the AC156 protocol is finally assessed using the FORM method, often used for the assessment of structural safety. The weakness of the AC156 protocol is evidenced, as well as guidelines for a safe application of such protocol to seismically certify unanchored components is provided.

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