16th World Conference on Earthquake Engineering, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 1707

Registration Code: S-P1461654252

SECOND LINE BACK-UP SYSTEMS FOR THE SEISMIC PROTECTION OF CLADDING PANELS IN RC PRECAST INDUSTRIAL BUILDINGS

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Abstract

Recent Italian earthquakes in L'Aquila (2009) and Emilia-Romagna (2012) revealed an inadequate seismic performance of many cladding panels in precast industrial buildings. Since the existing cladding-to-structure connections in several cases obviously do not possess adequate displacement and strength capacity to resist seismic loading, an improvement of the existing and a development of innovative systems is necessary.

Important steps toward the achievement of this goal have already been performed in the frame of the European FP7 project SAFECLADDING - Improved Fastening Systems of Cladding Panels for Precast Buildings in Seismic Zones [1]. Still additional research and development is needed to bring the new devices up to a level, when they could be used in practice.

Currently it is thus essential to find a simple and economically attractive back-up (retrofit) solution, which could be used in the existing structures as well as in new structures, where the traditional cladding connections still will be used. In the paper a newly developed restrainer system, designed to prevent a collapse of cladding panels upon the failure of existing connections is presented.

The restrainer system has been developed at the University of Ljubljana, Faculty of Civil and Geodetic Engineering in the frame of the recently concluded SAFECLADDING project. Such system consists of restrainers (steel or synthetic ropes) and anchoring elements which are used to attach the rope to the structural elements and cladding panels.

The strength and deformation capacity of the new restrainer system has been estimated by means of the set of static and dynamic experiments. The seismic demand has been estimated using closed-form expressions, which has been derived taking into account the main properties of their response. Finally, the proposed formulas have been evaluated based on the extensive numerical parametric study, where the structures were analyzed by means of the response history analysis.

Keywords: RC precast buildings, Cladding panels, Restrainers, Experiments, Analysis

1. Introduction

Recent Italian earthquakes in L'Aquila (2009) and Emilia-Romagna (2012) revealed an inadequate seismic performance of many cladding panels in precast industrial buildings. Since the existing cladding-to-structure connections in several cases obviously do not possess adequate displacement and strength capacity to resist seismic loading, an improvement of the existing and a development of innovative systems is necessary.

Important steps toward the achievement of this goal have been already performed in the frame of the European FP7 project SAFECLADDING - Improved Fastening Systems of Cladding Panels for Precast Buildings in Seismic Zones. Still additional research and development is needed to bring the new devices up to a level, when they could be used in practice.

Currently it is thus essential to find a simple and economically attractive back-up (retrofit) solution, which could be used in the existing structures as well as in new structures, where the traditional cladding connections still will be used. In the paper a newly developed second-line back-up system for the seismic protection of cladding panels in RC precast buildings is first briefly presented in Section 2. The system consists of special anchoring elements and ropes - restrainers.

The idea to use the restrainers as the second line back-up system is not new. In the 1971 San Fernando Earthquake in California some highway bridges collapsed due to the excessive longitudinal movement which occurred at expansion joints and supports [2]. Since then, the California Department of Transportation (CALTRANS) has installed longitudinal cable restrainers (Fig. 1) to prevent such collapses [2]. An extensive study on restrainer design procedures for multi-span simply supported bridges was presented in [2] by Randall et al. Many other related works published by several authors can be found in the literature, including [3-5].

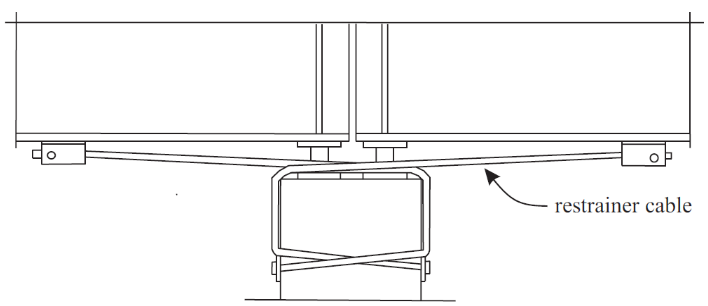

Fig. 1 A scheme of a restrainer system that is typically used for the seismic protection of multi-span simply supported bridges [6]

In precast structures different types of restrainers than those typically used for bridges are needed. The main reason is quite limited distance between the bare frame and the panels. Thus the length of the restrainers would be typically quite short (up to 70 cm). They do not fix the panels to the structure, but they are typically designed to be long enough to be activated upon the failure of the primary connections between panels and the primary structure. In this way they do not have any influence on the response of a building and its panels as long as the primary connections are operational. More details about the different types of primary connections and their seismic response can be found in [7].

The newly developed restrainer system (see Section 2) was examined experimentally and analytically. First the capacity of the system has been evaluated by means of the experiments overviewed in Section 3.

The new types of restrainers would be activated sporadically and for the periods of about $1/10^{th}$ of a second. The response of the primary structure and the panels at the moment of their activation is extremely complex. The main parameters which influence the response of the restrainers, the panels, and the primary structure at the moment of the impact are presented in Section 4. The closed formed equations which are to be used to estimate the maximum forces in the restrainers at the moment of their activation, and subsequently in the latter's design, are derived in Section 4.

In order to verify the analytical procedure, presented in Section 4, an extensive parametric study, using response history analysis (RHA), was performed, and the influence of several parameters affecting the impact forces in the restrainers was studied. This study is presented in Section 5.

2. Short description of the new second line back-up system

The proposed second-line back-up system is used to prevent the falling of panels after the failure of the primary connections between panels and the primary structure (see examples in Fig. 2). The system consists of a loose steel or synthetic fiber rope restrainer (see Fig. 3). The ropes are connected to omega and angular steel profiles which are fastened to the panels and beams/columns by means of swaged or resin-potted end terminations, respectively. Typical dimension of the concrete elements and the gap between the panels and beams/columns are given in Fig. 3. In the frame of the SAFECLADDING project, steel wire ropes with swaged end terminations and several types of synthetic fiber ropes with resin-potted end terminations were tested [8], however, material of the restrainer and the type of the end termination can be chosen by the designer based on the desired mechanical properties.

Fig. 2 The collapse of the cladding panels in an industrial precast building (left), and in a commercial building (right), both after the Emilia-Romagna earthquake (2012)

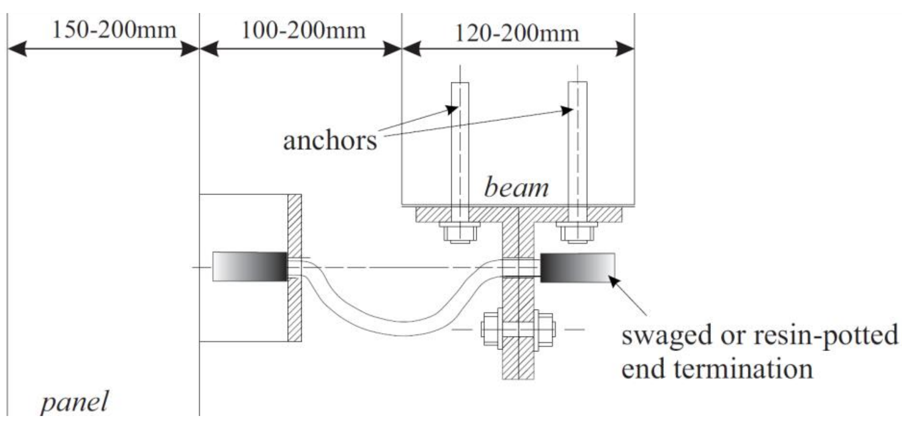

Fig. 3 A scheme of a restrainer system as a second-line back-up device for the prevention of the collapse of concrete cladding panels in the case of seismic events

3. The strength and the stiffness of examined restrainers

The strength of the proposed system depends primarily on the efficiency of the restrainers' terminations. Different types of terminations were examined, depending on the types of ropes (see Fig. 4). The capacity of connections was tested by means of uniaxial tension tests (see Fig. 5). Static and dynamic tests were performed. The diameter of the tested ropes was 6 mm and 8 mm. The synthetic ropes had the largest capacity (see Fig. 6). For example, the strength of the dyneema ropes (magenta points in Fig. 6) was in the range 40 kN – 55 kN, with an average of 47 kN. Their stiffness was about 2000 kN/m.

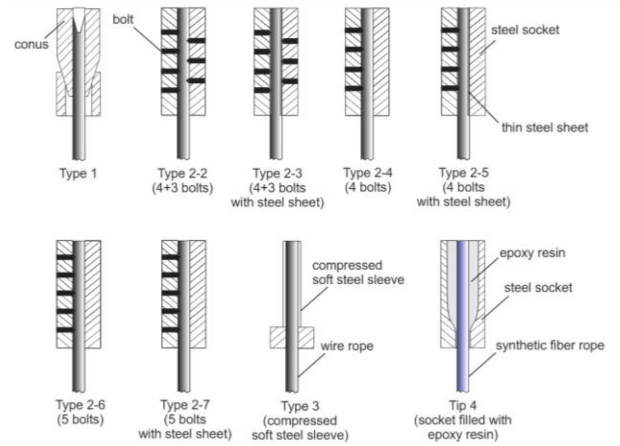

Fig. 4 Different terminations of the examined ropes

Fig. 5 The test of the capacity and stiffness

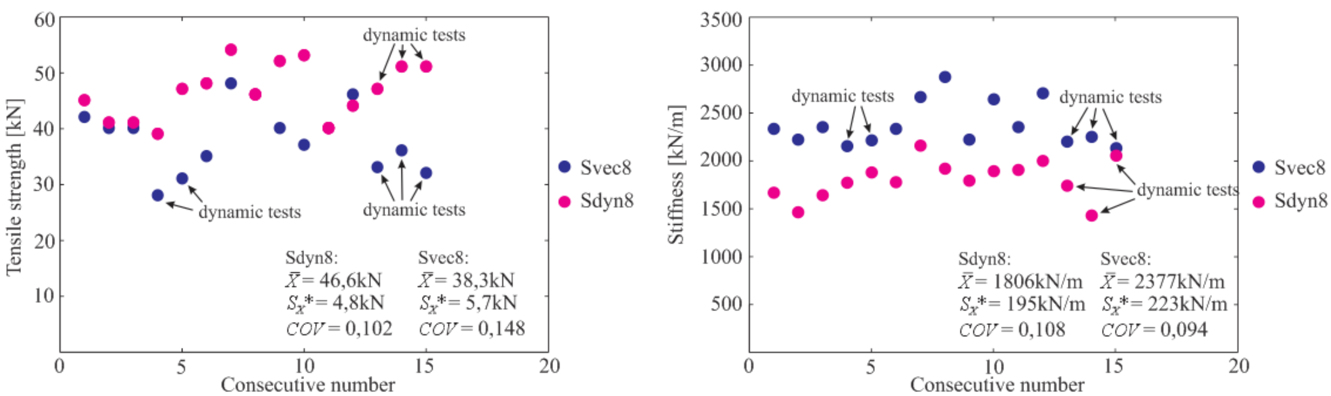

Fig. 6 Measured strength (left) and stiffness of the synthetic ropes

4. Analytical procedure for estimation of the forces, which could occur in short restrainers

In the following paragraphs equations, which can be used to estimate the maximum impact forces that can be expected in restrainers are derived. It should be noted that they can be used to estimate impact forces only if the restrainers have a short length (Fig. 7, left). In the case of long restrainers (restrainers that allow for panel inclinations larger than 5°) higher maximum impact forces could occur due to the force of gravity *G*, which induces an additional angular acceleration of the panel (Fig. 7, right). In such cases, it would be necessary to take into account the P-Delta effect (Fig. 7).

The dynamic response of the second line back-up system, during the short time within the restrainers are activated, can be described with acceptable accuracy using the relatively simple analytical model shown in Fig. 8. As illustrated in Fig. 8, the dynamic equilibrium of the system can be defined as:

$$f_I + f_E + f_D = 0 \qquad (1)$$

where f_I is the inertial force in the panel, which acts in a horizontal direction which is perpendicular to the plane of the panel; f_E is the force, which is activated in the restrainers, and f_D is the damping force.

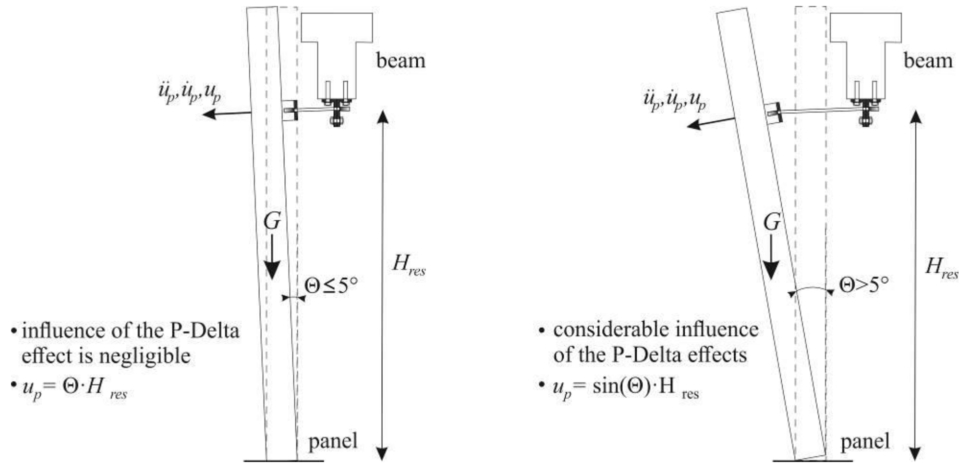

Fig. 7 The response of short (left) and long restrainers (right): Short restrainers do not permit any larger inclination of the panel - the P-Delta effect is therefore small or negligible. (left) Long restrainers permit significant inclination of the panel, so the P-Delta effect should be taken into account when estimating the maximum impact forces in the restrainers (right)

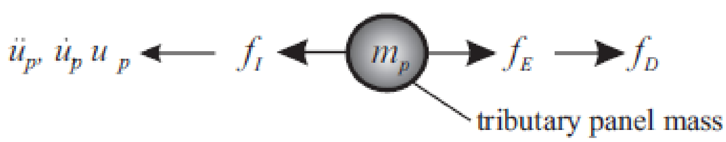

Fig. 8 An analytical model which can be used to estimate the maximum impact forces in restrainers (u_p, $\dot{u}_p$ and $\ddot{u}_p$ are the displacement, velocity, and acceleration of the panel at the height of the restrainer; f_I , f_E and f_D are the inertial, internal, and damping forces).

The inertial force f_I is equal to the product of the attributed panel mass per restrainer m_p and the acceleration of the panel in the out-of-plane direction $\ddot{u}_p$

$$f_I = m_p\, \ddot{u}_p \tag{2}$$

The force acting in the restrainer f_E is simply calculated by applying Hooke's law:

$$f_E = k_{res}\, u_r \tag{3}$$

where k_{res} is the stiffness of the restrainer and u_r is the relative displacement, which is equal to the deformation of the restrainer.

It is assumed that the damping force $f_D = 0$ taking into account that the damping of the secondary system (which consists of a cladding panel and two restrainers) does not have any significant influence on the impact forces in the restrainers.

Relative acceleration between the panel and the structure $\ddot{u}_r$ can be expressed as the difference between the absolute acceleration of the panel $\ddot{u}_p$ and the absolute acceleration of the main structure $\ddot{u}_s$:

$$\ddot{u}_r = \ddot{u}_p - \ddot{u}_s \tag{4}$$

Taking into account the equations (2) – (4), equation (1) can be expressed as:

$$m_p\ddot{u}_r + k_{res}u_r = -m_p\ddot{u}_s \quad (5)$$

The solution of equation (5) can be expressed as:

$$u_r = \frac{v_{r0}}{\omega}\sin(\omega t) + \frac{f_0}{k_{res}}\left[1-\cos(\omega t)\right] \quad (6)$$

where v_{ro} is the initial velocity, $\omega = \sqrt{\frac{k_{res}}{m_p}}$ and $f_0 = -m_p\ddot{u}_s$.

Taking into account the expression (3) and equations (6) the maximum force in the restrainer can be expressed as:

$$F_{res}^{\max} = f_0\left(1-\frac{f_0}{\sqrt{f_0^2+f_v^2}}\right) + f_v\sqrt{1-\frac{f_0^2}{f_0^2+f_v^2}} \quad (7)$$

where $f_v = v_{r0}\sqrt{k_{res}m_p}$

The stiffness of a restrainer k_{res} may be obtained from the product's technical specification, or can be measured (see Section 3). The stiffness of the short synthetic fiber-based restrainers tested within the scope of the SAFECLADDING project was around 2 MN/m (see Section 3). The attributed panel mass per restrainer m_p can be calculated taking into account the number of the installed restrainers. The estimation of the initial relative velocity v_{r0} (relative velocity between the panel and the structure just before the moment of activation of the restrainer) , and the estimation of the acceleration of the main structure during the activation of the restrainer $\ddot{u}_s$, are apparently not trivial tasks. The initial velocity is estimated based on the study, presented in the next section, the acceleration of the main structure was calculated from the acceleration spectrum.

5. Evaluation of the analytical procedure

The efficiency of the equations, presented in the previous section was tested by means of a parametric study based on response history analysis (RHA). The basic features and the results of this study are overviewed in Section 5.1. The same study was used to estimate the value of the initial velocity v_{r0} at the moment when the restrainers are activated. This study is presented in section 5.2. Finally, the parametric study was used to evaluate the expressions presented in the previous section. The comparison is presented in section 5.3.

5.1 Description and the main results of the parametric study

Two sets of RHA were performed:

1) First the response of the primary structure (Fig. 9) was analyzed using a set of 30 accelerograms, assuming that the structure is founded on soil type C (see Eurocode 8 [9] for more details), and that the peak ground acceleration is equal to PGA=0.25 g. Soil type C spectrum was chosen, since it is the most critical among likely scenarios (soil type D is quite rare). The accelerograms were selected from the European strong ground motion database [10] using the following selection criteria: the mean of the corresponding spectra (Fig. 10) should match the Eurocode 8 [9] spectrum for soil type C; the variance should be as small as possible; the epicentral distance should be between 4 and 60 km, the magnitude between 4 and 8, and the scale factor not larger than 3. This was achieved using a special optimization technique proposed by Jayaram et al. [11].

2) In the second set of RHA, an assemblage consisting of the panel and two restrainers (one panel is typically supported by two restrainers; one restrainer is provided in each of the top corners) was subjected to 30 relative acceleration histories calculated during the first set of RHA at the top of the primary structure (Fig. 9).

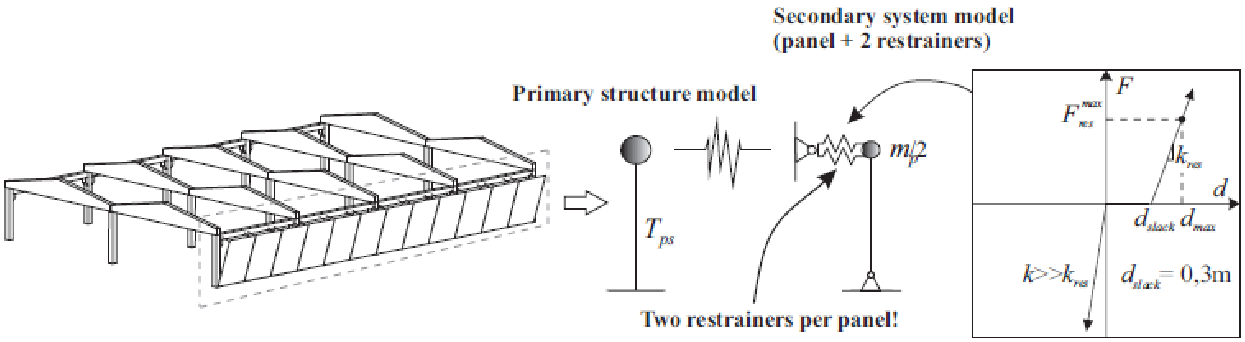

Fig. 9 Models of the primary structure and of the secondary system (panel and 2 restrainers)

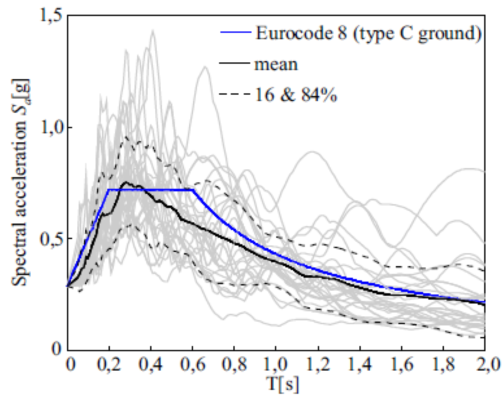

Fig. 10 Spectra for the set of 30 selected accelerograms and the target Eurocode 8 spectrum

The model of the assumed secondary system consisted of three elements (Fig. 9). A standard elastic beam-column element was used to model the panel. The other two elements were used to model the response of the restrainers and the impact between the panel and the primary structure.

Typical response histories for the different variables (displacement, acceleration, velocity) are presented in Fig 11. The displacement response history of the panel and of the primary structure are shown in Fig. 11a. It can be clearly seen that the relative displacement between the panel and the structure does not exceed a value of 0.3 m.

The response histories of the force acting in the restrainer and the relative velocity between the panel and the structure are presented in Fig. 11b. It was found in Section 4 that the forces acting in restrainers depend on the initial relative velocity at the moment when the restrainers are activated. This is clearly visible in Fig. 11b, where the correlation between the relative velocity and force acting in the restrainer is evident.

The acceleration response histories for the structure and the panel are shown in Fig. 11c. A considerable instant increase in the panel's acceleration can be seen at the moment of impact between the panel and the primary structure, as well as at the moment when the restrainers are activated. It is also important to observe that the acceleration of the primary structure is small compared to that of the panel (this ratio is about 0.1). It does not significantly vary during the activation of the restrainer.

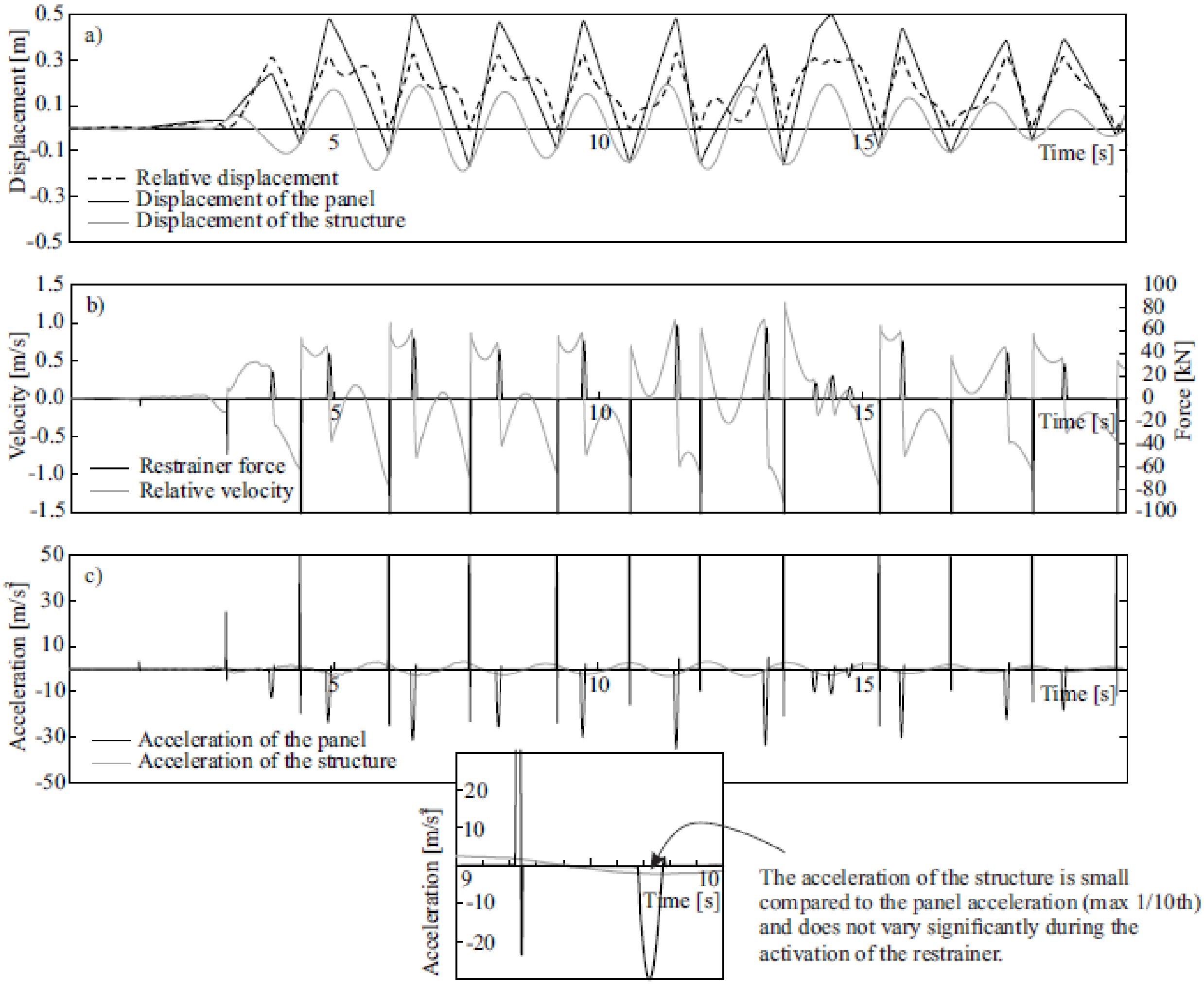

Fig. 11 Results of RHA for a single accelerogram: response history for displacements, accelerations, relative velocity, and the impact force acting in the restrainer

The medians and 84th percentiles of the maximum impact forces in a single restrainer, corresponding to different input parameters (the panel mass, the restrainer's stiffness k_{res}, the period of the primary structure T_{ps} and the damping ratio ξ) are presented in Figs 12 - 14. The median forces in the restrainers with a stiffness of 2 MN/m are in the range from 65 kN to 100 kN, and 25 kN to 65 kN, for primary structures with a period of vibration of T_{ps}=1.0 s and T_{ps}=2.0 s, respectively. The results presented in Figs 12 - 14 confirm the correlation between the maximum impact force in the restrainer and the panel mass, as well as the correlation between the maximum impact force in the restrainer and the restrainer's stiffness. Maximum forces in restrainers decrease when the period of the primary structure T_{ps} increases.

Closer inspection of Figs. 12 - 14 also confirms that the damping ratio of the secondary system does not have a significant influence to the forces in the restrainers, particularly when it is compared to the other investigated parameters. This assumption was used to derive the maximum forces in the restrainers in Section 4.

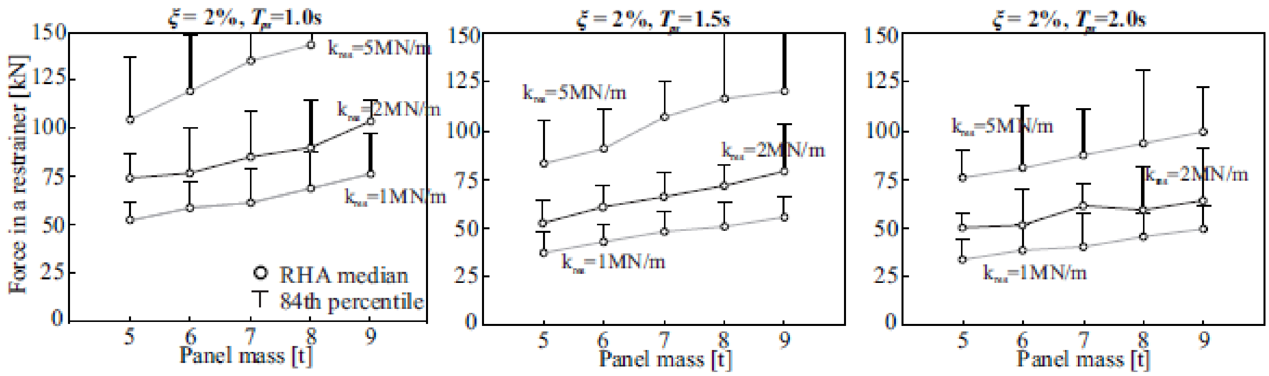

Fig. 12 Results of the RHA: the maximum impact forces in a restrainer for different input parameters, including the panel mass, the restrainer stiffness k_{res}, period of the primary structure T_{ps} and an assumed damping ratio of $\xi = 2\%$.

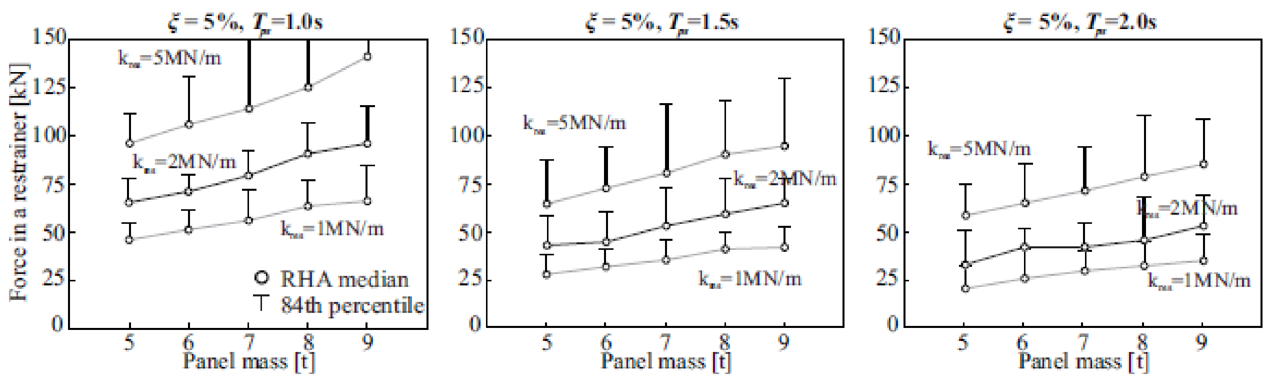

Fig. 13 Results of the RHA: the maximum impact forces in a restrainer for different input parameters, including the panel mass, the restrainer stiffness k_{res}, period of the primary structure T_{ps} and an assumed damping ratio of $\xi = 5\%$.

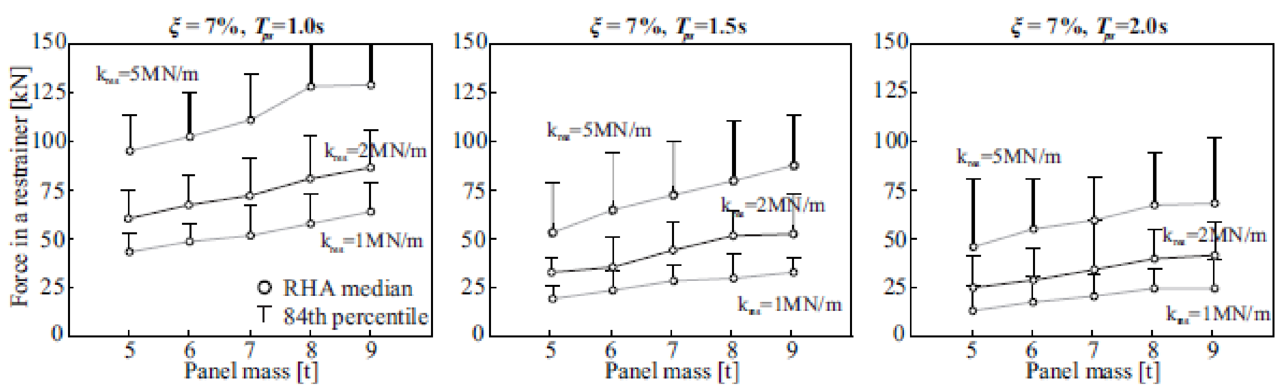

Fig. 14 Results of the RHA: the maximum impact forces in a restrainer for different input parameters, including the panel mass, the restrainer stiffness k_{res}, period of the primary structure T_{ps} and an assumed damping ratio of $\xi = 7\%$.

5.2 Estimation of the initial velocity v_{ro} at the moment when the restrainers are activated

One of the crucial parameters that influences the maximum forces in a restrainer is the initial relative velocity between the primary structure and that of the panel just before activation of the restrainer v_{r0} (see also Eq. 7). Since the panel and the primary structure move independently before the restrainer is activated, the estimation of the relative velocity v_{r0} is not a trivial task. In this subsection some suggestions are given how the relative velocity v_{r0} could be estimated with sufficient accuracy. For this purpose, the results of the RHA, which are presented in the previous subsection will be addressed.

Based on the results of the RHA, the ratio between the maximum relative velocity between the structure and the panel just before activation of the restrainer v_{r0}, as well as the maximum velocity of the primary structure $\dot{u}_{s,\max}$ is estimated first. It should be noted that just before the activation of the restrainer, the relative velocity between the primary structure and the panel v_{r0} is not necessarily equal to the maximum relative velocity between the primary structure and the panel $\dot{u}_{r,\max}$. Although this is not the most likely case, a conservative assumption that the initial velocity v_{ro} is equal to the maximum relative velocity between the primary structure and the panel typically leads to a good estimation of the maximum forces in the restrainers. This is confirmed in the next subsection based on the comparison of the numerical analyses (described in section 5.1) and analytical procedure, presented in Section 3.

Taking into account the previously described assumption about the initial relative velocity v_{ro}, the ratio of the maximum velocity of the primary structure $\dot{u}_{s,\max}$ and maximum relative velocity between the primary structure and the panel $\dot{u}_{r,\max}$ was evaluated taking into account results of the RHA analyses, presented in the previous subsection. These ratios are presented in Fig. 15.

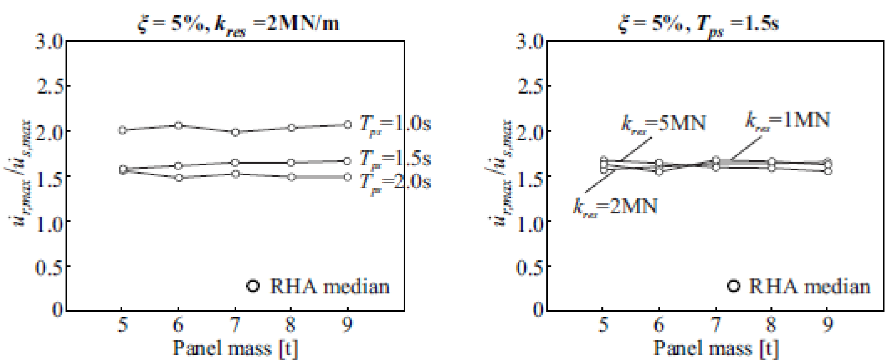

Fig. 15 The ratio between the maximum recorded relative velocity $\dot{u}_{r,\max}$ and the maximum structure velocity $\dot{u}_{s,\max}$, as recorded by RHA: the ratio corresponding to different periods of the primary structure T_{ps} (left diagram) and the ratio corresponding to different restrainer stiffness k_{res} (right diagram).

The left hand diagram in Fig. 15 clearly illustrates the influence, which the period of the primary structure T_{ps} has on the ratio between the maximum relative velocity and the maximum velocity of the primary structure. The ratio was calculated for a constant restrainer stiffness of k_{res}=2 MN/m and panels' mass in the range 5 t to 9 t. On average it was equal to 2.0, if the period of the primary structure was T_{ps} =1.0 s. When this period was increased to T_{ps} =1.5 s and T_{ps} =2.0 s, the average ratio decreased to 1.6 and 1.5, respectively.

On the other hand, the right hand diagram, presented in Fig. 15 (corresponding to the period T_{ps}=1.5 s and different stiffness of restrainers) demonstrates that the restrainer's stiffness k_{res} is not as important as the period of the primary structure T_{ps}. The ratio of 1,6 was obtained regardless of the restrainers' stiffness.

Taking into account previous observations it has been concluded that the initial relative velocity v_{ro} can be estimated based on the maximum velocity of the structure $\dot{u}_{s,\max}$ and its ratio to the maximum relative velocity $\dot{u}_{r,\max}$. It should be further noted that the maximum velocity of the structure $\dot{u}_{s,\max}$ was estimated taking into account the spectral velocity, defined as:

$$\dot{u}_{s,\max} = \frac{S_a\left(T_{ps}\right)T_{ps}}{2\pi} \tag{8}$$

Where $S_a(T_{ps})$ is a spectral acceleration corresponding to the period of the primary structure T_{ps}. In the presented study Eurocode 8 acceleration spectrum, corresponding to the soil type C was taken into account (as it was explained in the previous subsection).

5.3 Evaluation of the analytical procedure by means of the parametric study

Maximum forces in the restrainers, predicted using equation (7) were evaluated by the results of the numerical parametric study, presented in section 5.1. The comparison is presented in Fig. 16. Results correspond to different restrainer stiffness k_{res}, different masses of the panel and different periods of vibration of the primary structure T_{ps}.

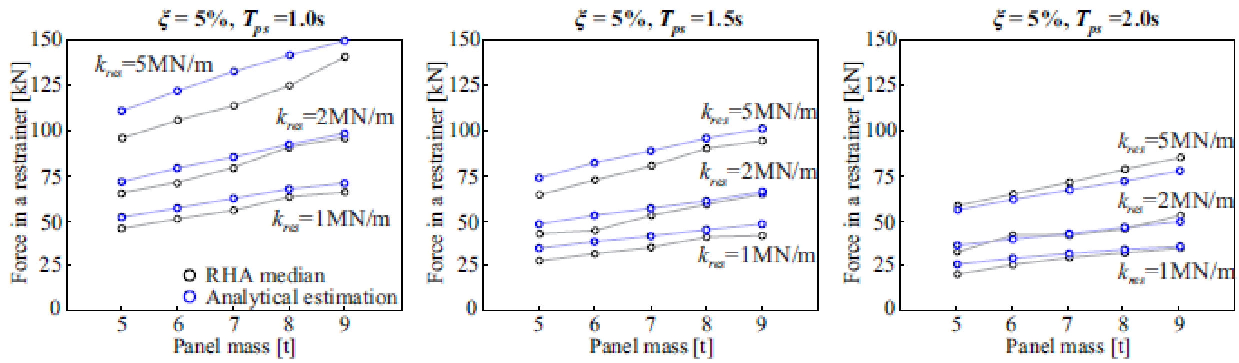

Fig. 16 The match between the numerically obtained maximum forces in restrainers and maximum forces in restrainers derived using the proposed analytical formula

The match between forces, derived numerically and analytically, is good, particularly if the simplicity of the proposed formula (Eq. 7) is taken into account. The largest discrepancy (about 20 %) was observed in the cases where the period of vibration of the primary structure was T_{ps} = 1,0 s and the restrainer's stiffness was k_{res} = 5 MN/m (the top blue and black curves in the left hand diagram in Fig 16). The proposed Eq. (7) somewhat overestimates maximum forces in restrainers for all analyzed structures with period T_{ps} = 1 s.

The same conclusions can be obtained for structures with period T_{ps} = 1,5 s (central diagram in Fig. 16). However, the match with the numerical results is better than in structures with the period of T_{ps} = 1,0 s. The best match of the numerically and analytically derived maximum forces in the restrainers was observed in structures with periods of T_{ps} = 2,0 s.

In all cases but one, the proposed formula overestimated the forces in the restrainers. The only exemption are structures with period of T_{ps} = 2 s, and the restrainers with stiffness 5 MN/m. In these cases, the analytical procedure slightly underestimated forces in the restrainers, but this discrepancy was small (about 8%).

It is worthy to note that the proposed analytical procedure particularly well estimates the forces in the restrainers with stiffness of 2 MN/m. Note that this is the stiffness which is typical for the most efficient types of restrainers (see Section 3).

6. Conclusions

Although the concrete cladding panels are non-structural elements, their failure can cause outmost direct and indirect damage. This was also revealed in the recent earthquakes in the northern Italy. It has been demonstrated within the European FP7 project SAFECLADING that their response to strong earthquakes depends mainly on their connections with the main structural system. It was found out that the connections, which are typically used in Europe cannot prevent their failure when the structures are subjected to moderate and strong earthquakes. The seismic strengthening of the cladding panels is, therefore, needed for the considerable number of existing RC precast buildings (note that about 50 million m^2 of such structures is built in Europe annually).

The second line back-up system consisting of the steel or synthetic restrainers that tie the cladding panels to the main structural system of precast buildings has been developed at the University of Ljubljana. The system is designed to be activated upon the failure of the primary connections between the panels and the main structural system.

The restrainers consist of different types of ropes. They were examined experimentally and analytically. While their strength and the stiffness have been determined by experiments, the demand (maximum forces) were derived analytically. Since the response of the proposed system is very complex, the new analytical procedure, which can be used to define the maximum forces in the restrainers has been developed. Since it is quite simple it is suitable for the design practice.

The proposed analytical procedure has been evaluated by means of the extensive numerical parametric study, which included the nonlinear response history analysis of typical RC precast structures. It has been proved that the proposed procedure is reliable in all typical cases included in the study.

Acknowledgements

The research was supported by the SAFECLADDING project "Fastening Systems of Cladding Wall Panels of Precast Buildings in Seismic Zones" (Grant agreement no. 314122) in the framework of the Seventh Framework Programme (FP7) of the European Commission.

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