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Preliminary assessment of PreWEC-like systems made by cross-laminated timber panels and steel columns

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Abstract

In recent years many types of seismic-resistant structural systems have been developed to improve resilience through self-centering ability. One of such system for reinforced concrete buildings is the "Precast Wall with End Columns" system (PreWEC). Starting from this concept, various studies have been carried out to evaluate the possibility of adopting a mixed system with steel columns and cross laminated timber walls. Previous experimental tests have highlighted the difficulty of cross laminated timber walls to cope with the compressive stresses arising during the rocking motion. The purpose of this paper is to evaluate the potential benefits of adopting a PreWEC-like system made by cross laminated timber panels connected to steel columns in a building with light-weight composite steel-timber floors. The design procedure considered herein follows a displacement-based design approach and a validation by means of non-linear analyses. A case study resembling a 5-storey building located in a region of high seismicity was selected. A comparative study between the timber-steel and classical PreWEC system was performed, accompanied by along a Life Cycle Assessment "from cradle to gate". The results highlight the suitability of PreWEC-like systems with cross laminated timber panels and steel columns and the conservative results in terms of roof drift obtained from the selected design procedure. In addition, the embodied environmental impact of the analyzed timber structural systems is also lower than the traditional reinforced concrete one in most of the assessed impact indicators.

Keywords: Rocking systems; Self-centering; Cross-laminated wall panels; Timber-steel composite floors; Sustainability.

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1. Introduction

Previous research has shown that the development of unbonded post-tensioned rocking walls can help to reduce the seismic vulnerability and therefore to increase the structural resilience of buildings in seismic areas. Since rocking systems are characterized by low energy dissipation capabilities (Holden and Mander, 2003), alternative structural systems have been developed such as the hybrid wall system (Holden and Mander, 2003), the jointed wall system (Priestley et al., 1999) and the Precast Wall with End Column (PreWEC) system (Aaleti and Sritharan, 2007). This latter consists of a single precast concrete wall connected to two end columns by means of special connectors which enables the system to dissipate energy during an earthquake. The columns can be made of steel, reinforced concrete (RC) or composite sections such as concrete filled steel pipes. Both walls and columns of this structural system are anchored to the foundation by unbonded post-tensioning tendons designed to remain elastic when subjected to events up to design level earthquake.

Research on low-damage earthquake-resistant structural systems with bearing elements made in cross-laminated timber (CLT) started lately focusing on frame-type systems (Hashemi et al., 2016; Iqbal, 2015) and re-centering wall systems (Ganey et al., 2017; Akbas et al. 2017). It has been found that, due to the reduced weight of the CLT systems, additional post-tension cables are required to obtain a complete re-centering. Furthermore, with the addition of energy dissipators, a flag behavior hysteresis is attained. The inadequacy of the CLT re-centering walls was highlighted for applications in areas of high seismicity due to the inevitable loss of stiffness of the timber rocking joint during an earthquake; thus, limiting advantages provided by these systems, such us light-weight earthquake-resistant structural members. Some researchers have also studied the possibility of coupling two CLT panels with U-shape Flexural Plate (UFP) dissipators (Akbas et al., 2017; Moroder et al. 2018) to increase the wall seismic capacity while assuming thickness of the panels over the standard tabulated values.

The aim of the paper was to evaluate the feasibility of a PreWEC-like system made by CLT wall panels connected to steel columns in a building featuring light-weight composite steel-timber floor diaphragms. Results from the as-built system are compared against to those obtained from adopting a precast reinforced concrete solution. The displacement-based design approach proposed by Aaleti and Sritharan (2011) for PreWEC systems with reinforced concrete walls and columns was adapted to account for actual properties of the timber-steel structural assembly. Non-linear static and dynamic analyses were carried out on the numerical model of a single PreWEC-like system designed for a five-story building in a high seismic area. Finally, preliminary considerations were made regarding the environmental impacts of PreWEC-like systems with CLT walls and steel columns compared to the traditional system with precast RC elements. These considerations were derived through a Life Cycle Assessment (LCA).

2. Materials and design criteria

2.1. Light-weight composite steel-timber floors

The studied lightweight timber-based composite flooring system features an innovative modular design, as shown in Fig 1. This consists of prefabricated composite modular units, each made of CLT panels connected to twin cold-formed custom-built steel beams via discrete shear connectors installed at uneven spacing in order to account for the longitudinal shear stress distribution in the floor (Owolabi and Loss, 2022). The applicable shear connectors include self-tapping screws of various inclination angles and a combination of perforated steel plates bonded using an epoxy-based grout (Loss and Davison, 2017). An omega-shaped beam profile is adopted when self-tapping screws serve as shear connectors, while a U-shaped beam profile is preferred for solutions with grouted steel plate-types shear connectors (Loss et al., 2016a; 2016b).

The fundamental composite units are connected along their slab edges through self-tapping screws installed at regular spacings and the steel beams are bolted to the primary beams of the main structural frame, with the capability for rotational stiffness adjustments at varying the preload on bolts. This flooring system suits residential applications, and its mode of assembly enhances the easy disassembly, reuse, and repurposing of its components (Loss et al., 2018).

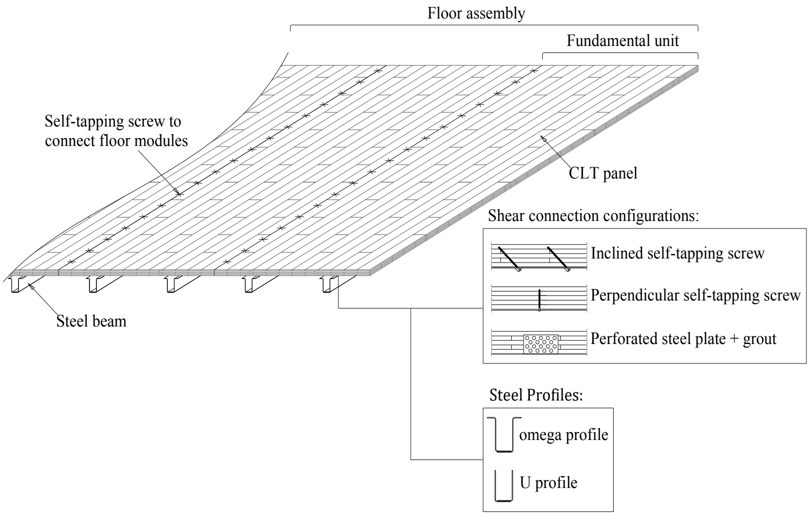

Fig. 1. Composite steel-timber floor assembly description

2.2. Design procedure

The procedure considered herein is based on the guidelines developed by Aaleti and Sritharan (2011) for PreWEC systems with reinforced concrete walls. The procedure has been adapted for the design of PreWEC-like systems with CLT wall panels and steel columns. CLT panels have been reinforced with steel plates nailed at their base to improve the performance in the compressed region during rocking. The procedure starts from the definition of the mechanical properties of the construction materials, then the wall dimensions are preliminary established considering for instance architectural constraints or design values reported in the literature (e.g., Stanton and Nakaki, 2002). For a given design drift, herein taken as 2%, the bending moment demand (M_d) is determined following a displacement-based design (DBD) approach. Hence, the procedure allows establishing the definitive geometry of the system, the required quantity of post-tensioning, the number of dissipators as a function of the bending moment percentage assigned to them and the maximum compressive force (N_{co}) at the base of the wall.

N_{co} allows to determine the minimum cross-section (A_p) of one of the two steel plates (one at each side) nailed to each end of the CLT wall. By setting the thickness (t_p) of the plate, it is possible to determine its width (L_p)

$$A_p = \frac{N_{co}}{2f_{yd}} \tag{1}$$

$$L_p = \frac{A_p}{t_p} \tag{2}$$

Regarding the vertical extension of the steel plate, a 45 ° distribution of the compressive stresses along the wall is assumed considering the rocking interface as a discontinuity region. At this point, it is possible to estimate the number of nails required:

$$n_b = \frac{N_{Co}}{2R_{Vk}} \tag{3}$$

Where R_{vk} is the shear strength of the nail.

Once the geometry of the steel plates has been established, the capacity of the CLT wall beyond the reinforcing plate must be assessed.

Considering the combined axial load and bending moment:

$$\left(\frac{\sigma_{cd}}{f_{cd}}\right)^2 + \frac{\sigma_{md}}{f_{md}} \leq 1 \tag{4}$$

$$\sigma_{cd} = \frac{N_{Ed}}{L_w t_w} \tag{5}$$

$$\sigma_{md} = \frac{6M_2}{t_w {L_w}^2} \tag{6}$$

$$M_2 = M_1 - F_h H_w \tag{7}$$

Where f_{cd} and f_{md} are the design compressive strength and the design bending strength of the CLT panel, respectively; N_{Ed} is the effective compression at the base of the wall; L_w and t_w are the width and thickness of the wall, respectively. M_2 is the value of the bending moment in the cross-section above the reinforcing steel plate while M_1 and F_h are the required base moment and the base shear, respectively

Considering the shear capacity:

$$\tau_d = \frac{3}{2}\frac{F_h}{k_{cr} L_w t_w} \leq f_{v,d} \tag{8}$$

Where k_{cr}, is a reduction factor equal to 0.67 and f_{vd} is the design shear resistance of the CLT.

3. Parametric analysis

A parametric analysis was conducted to establish the influence of the design parameters on the final sizes of the CLT wall; specifically, its width, as the thickness was taken equal to 0.28m consistently with the standard maximum thickness of the CLT panels processed in Italy, although a higher thickness could be obtained if required.

A single PreWEC-like system was analyzed considering: a floor tributary area equal to 12mx12m; a percentage of the bending moment assigned to the connectors (M_{con},) equal to 10%, 20% and 30% of the total bending moment demand (M_d); a story number equal to 3, 5, and 7; the design seismic inputs with peak ground acceleration (PGA) equal to 0.2g and 0.4g. In addition, two types of floors were considered: a light-weight timber-steel floor (3.9 kN/m^2) and a precast floor (7.4 kN/m^2). The results are reported in Fig. 2 and Fig. 3 as a function of the story number in terms of the design width (L_w) of the wall.

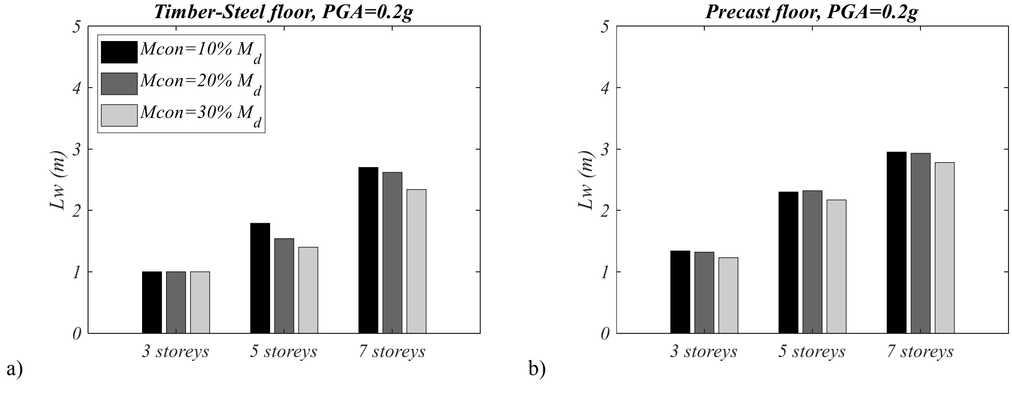

Fig. 2. Parametric analysis results for PGA equal to 0.2g: a) considering a timber-steel floor type, b) considering a precast floor type.

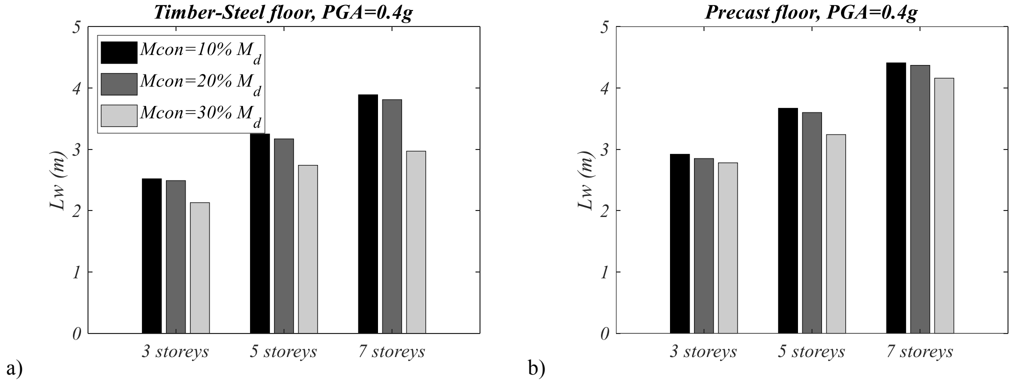

Fig. 3. Parametric analysis results for PGA equal to 0.4g: a) considering a timber-steel floor type, b) considering a precast floor type.

Considering the cases with PGA equal to 0.2g (Fig. 2), L_w decreases as the percentage of moment assigned to the connectors increases: going from 10% to 30% of M_d there is a maximum wall length variation of 22% for the 5-story building with timber-steel floor. L_w increases with the number of floors of the building with a maximum variation of 79% (10% M_d, from 3 to 5 stories). Furthermore, it can be observed how L_w increases if we consider a concrete floor as the seismic mass increases.

Considering the cases with PGA equal to 0.4g (Fig. 3), an increase in L_w is generally observed compared to the case of PGA equal to 0.2g: a maximum increase of 54% (Timber-steel floor) and 51% (precast floor) is observed. As in the previous case, a reduction of L_w is observed as the percentage of moment assigned to the connectors increases. Going from 10% to 30% of M_d there is a maximum wall length increase of about 24% and 6% for the timber-steel floor and concrete floor cases, respectively.

4. Case study analysis and results

To assess the performance of the investigated structural system, a finite element (FE) analysis of a case study building was carried out. The PreWEC-like system considered refers to a 5-story building and a PGA equal to 0.4g. Based on the aforementioned results, a CLT wall with cross-section equal to 3mx0.28m was analyzed.

The FE model and the analyses were carried out with the software MidasGen (2020). The columns and the wall were modeled as beam elements; the post tension cables were modeled as truss elements. For the modeling of the rocking interface, a multi-spring approach was used (e.g., Belleri et al., 2013): i.e. a bed of springs with compression-only behavior at the interface between the foundation and the vertical structural element (i.e. the wall or the columns). The dissipators chosen were “O-connectors”, placed in the FE model as “general links” with elastic-perfectly plastic behavior (Δ_y = 0.00316m, F_y = 23.66kN, Δu = 0.0632m) in the vertical direction and axially rigid in the horizontal direction. Non-linear static and time history analyses were carried out; the latter considering an artificial spectrum-compatible accelerogram (Fig. 4c).

The results of the analyses are reported inf Fig. 5 in terms of capacity curve and roof displacement over time. It is possible to notice a stable behavior without any loss of stiffness up to the target displacement of 0.3m which corresponds to a roof drift of 2%. The seismic response of the system is completely re-centering and the maximum displacement reached at the roof is about half of the design displacement showing that the adopted design procedure provides conservative results.

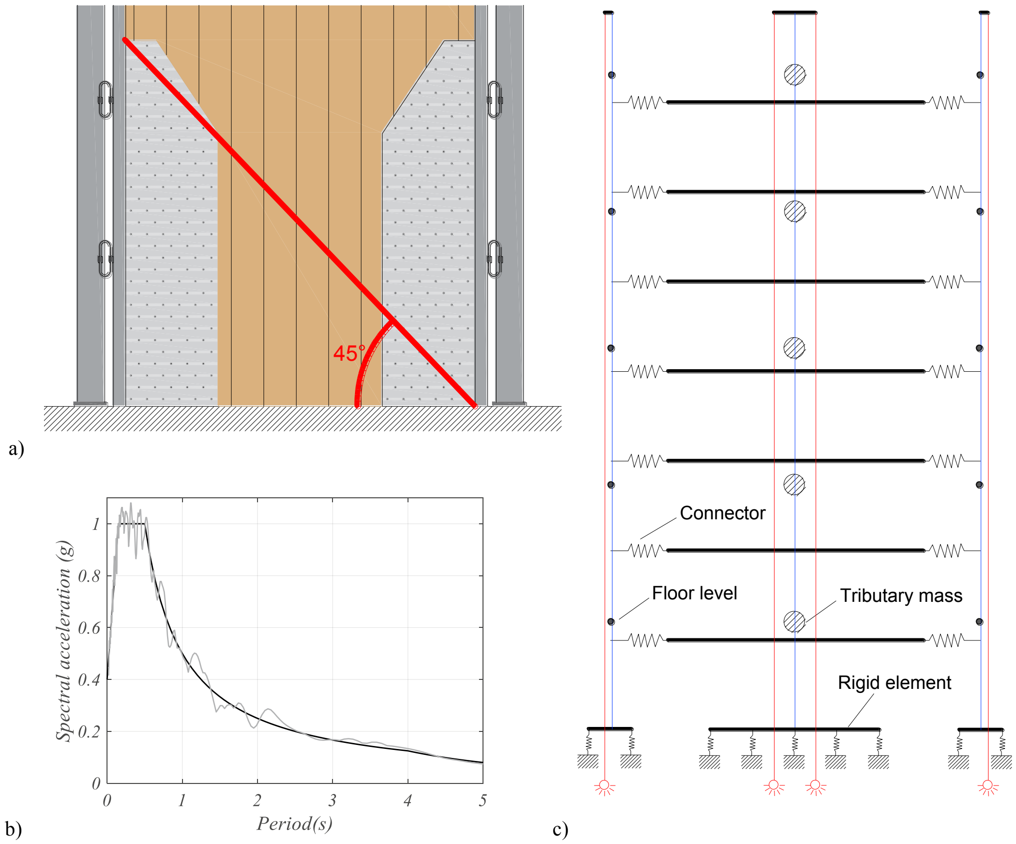

Fig. 4. a) Schematic details of the PreWEC-like system; b) pseudo-acceleration response spectrum; c) finite element model scheme.

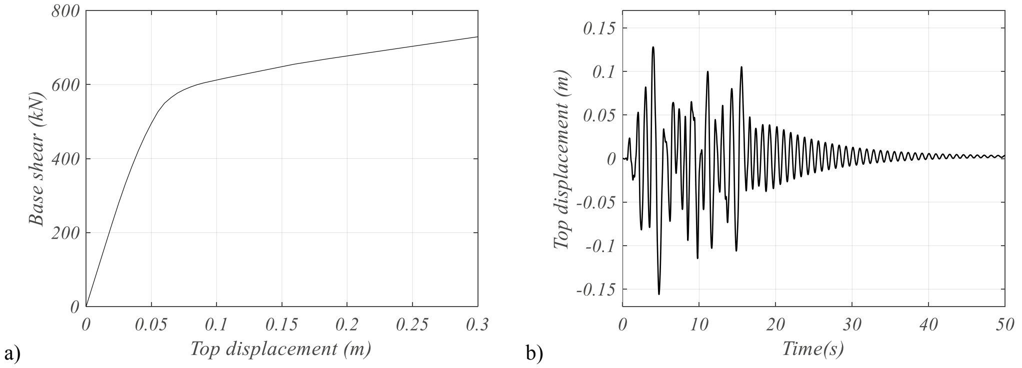

Fig. 5. Analyses results: a) capacity curve of the pushover analysis; a) Top displacement-time curve.

5. Preliminary considerations on the environmental impact

Finally, in order to take account of the significance of the environmental impacts of the proposed structural system, the embodied impacts has investigated through a Life Cycle Assessment (LCA) based on Environmental Products Declarations (EPD) data. Various authors identify EPDs as a preferable data source for cradle-to-gate LCA rather than using commercial LCA databases: in fact, EDPs provide more transparency and consistency given that they are based on standardized processes and provide more specific and more reliable information about products from the manufacturers (Strazza et al., 2016; Santero and Hendry, 2016). Herein, the embodied impact indicators were taken from One Click LCA (Bionova, 2022), selecting EPD associated with the materials and products adopted in the study. In particular, the impacts are measured cradle-to-gate, that means the inputs and outputs flow are taken from the confines of the cradle up to the factory gate of the final processing operation. Consequently, some portions of the total embodied impacts are excluded, such as those related to site delivery (included in cradle-to-site) and to end of life (included in cradle-to-grave). In the current definition of EPD contents, this latter information is not available, and broader estimates by LCA software simulation are therefore required in future.

Fig. 6 shows the embodied impacts for both RC (made with C45/55 class concrete considering a CEMI 52.5R) and CLT (made with C24 strength class panels) structural systems in function of 7 impact indicators (Global Warming Potential - GWP, Ozone Depletion Potential - ODP, Photochemical Ozone Creation - POCP, Acidification Potential - AP, Eutrophication Potential - EP, Depletion of abiotic resources- elements - ADPE, and Depletion of abiotic resources-fossil fuels, ADPF) and two parameters of resources use (Total use of renewable primary energy resources – PERT, and Total use of non-renewable primary energy resources - PENRT).

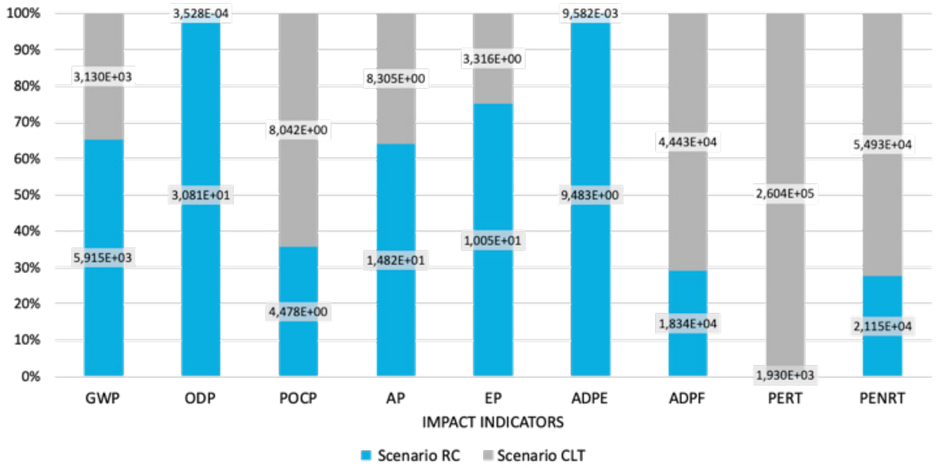

Fig. 6 Impact indicators and use of resources parameter of the analyzed systems (Global Warming Potential, GWP [kg CO2 eq], Ozone Depletion Potential, ODP [kg CFC-11 eq], Photochemical Ozone Creation, POCP [kg C2H4 eq], Acidification Potential, AP [kg SO2 eq], Eutrophication Potential, EP [kg PO 3 eq], Depletion of abiotic resources- elements, ADP-elements [kg Sb eq] AND Depletion of abiotic resources-fossil, ADP-fossil fuels [MJ]: Reinforced concrete versus Cross-Laminated Timber.

The results revealed that the RC-system impacts are higher than those of the CLT-system for 5 of the 7 impacts indicators assessed, while the CLT-system impacts produces greater impacts regarding the use of renewable and non-renewable primary energy resources. One of the key strategies to reduce the embodied impacts of the RC solution could be the adoption of low carbon building materials (Lukić et al., 2021), as for instance by including recycled aggregates in the mix design: a rough assessment considering a substitution of the selected concrete with 30% of recycled content determines a reduction in CO_2 of about 23%.

6. Conclusion

In this paper a feasibility study of PreWEC-like system made of cross laminated timber (CLT) wall panels and adjacent steel columns was presented. A design procedure adapted from the literature was considered to size the members, the amount of post-tensioning and of energy dissipators. The geometry of the system was investigated through a parametric study as a function of the height of the building, the weight of the floors, the amount of bending moment assigned to the connectors and the level of seismic input. The results confirmed the feasibility of PreWEC-like systems having elements with comparable dimensions to a traditional precast system, particularly in the case of light-weight floors made by composite steel-timber elements. The results of the parametric analyses were further validated through nonlinear static and dynamic analyses considering a planar finite element model for a given case study. The results show the effectiveness of the re-centering behavior but highlight the conservativeness of the considered design procedure. Finally, some preliminary considerations have been obtained from a Life Cycle Assessment in function of 7 impact indicators and 2 resource-use parameters. Herein, only the embodied impact of the materials adopted in the two lateral force resisting systems has been considered. The broadening of the scope of the study to other life cycle stages, such as transport and end of life, is an important focus of further research to provide a valuable and robust tool to support sustainable design choices.

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