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FEASIBILITY OF PINNED-BASE CONNECTIONS FOR DEMOUNTABLE PRECAST FRAME BUILDING SYSTEMS

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ABSTRACT

In recent Canterbury earthquakes, structures have performed well in terms of life safety but the estimated total cost of the rebuild was as high as $40 billion. The major contributors to this cost are repair/demolition/rebuild cost, the resulting downtime and business interruption. For this reason, the authors are exploring alternate building systems that can minimize the downtime and business interruption due to building damage in an earthquake; thereby greatly reducing the financial implications of seismic events. In this paper, a sustainable and demountable precast reinforced concrete (RC) frame system in which the precast members are connected via steel tubes/plates or steel angles/plates and high strength friction grip (HSFG) bolts is introduced. In the proposed system, damaged structural elements in seismic frames can be easily replaced with new ones; thereby making it an easily and quickly repairable and a low-loss system. The column to foundation connection in the proposed system can be designed either as fixed or pinned depending on the requirement of strength and stiffness. In a fixed base frame system, ground storey columns will also be damaged along with beams in seismic events, which are to be replaced after seismic events; whereas in a pin base frame only beams (which are easy to replace) will be damaged. Low to medium rise (3-6 storey) precast RC frame buildings with fixed and pin bases are analyzed in this paper; and their lateral capacity, lateral stiffness and natural period are scrutinized to better understand the pros and cons of the demountable precast frame system with fixed and pin base connections.

KEYWORDS

Precast concrete, demountable systems, sustainable structures, low loss system, base fixity.

INTRODUCTION

Monolithic reinforced concrete (RC) building systems and conventional pre-cast concrete building systems using "wet joints" are susceptible to damage under seismic excitations, which makes buildings using these systems incur significant loss in earthquakes mainly because of the substantial downtime in addition to the repair cost required to fully restore the functionality of the damaged building. Moreover, these buildings are not sustainable in terms of adaptable architecture. Cast-in-situ structures are to be demolished at the end of the building's life span or when it is decided to construct a new building at that site for any other reasons. It is shown that the demolition of concrete structures requires a great amount of energy and money. Moreover, demolition process is environmentally very unfriendly and causes extensive wastage of materials (Reinhardt 2012). For these reasons, the authors are exploring alternate RC building systems which are sustainable, flexible, demountable, and incur minimum downtime and seismic losses.

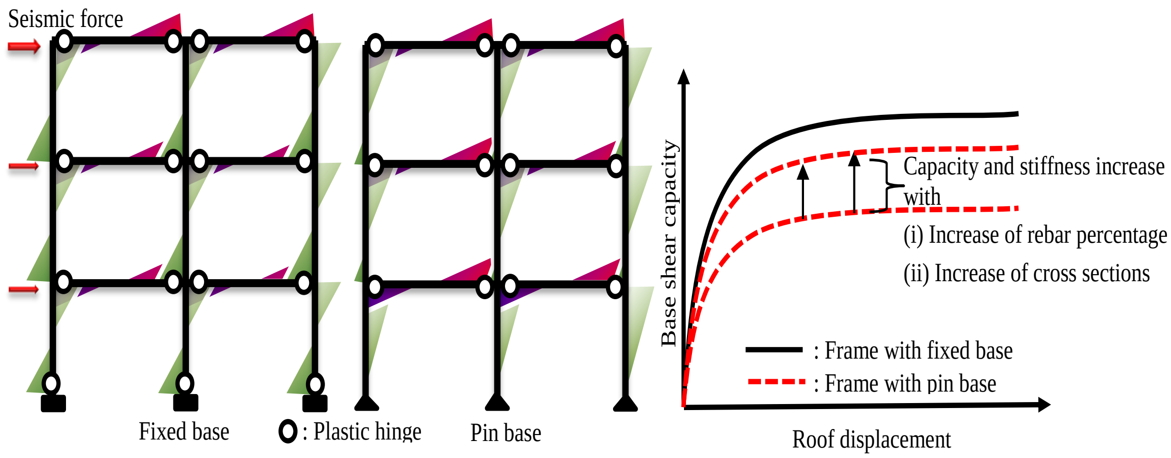
Precast concrete construction offers potential advantages like quicker construction, better quality and durability, reduction in site labour, and reduction in site formwork. Structural behaviour of precast concrete structures is different from cast-in-situ concrete structures. From a general point of view, there are two alternative ways to design precast concrete structures. One choice is to interconnect the precast concrete elements predominantly by hinged connections, whereas the other alternative is to emulate monolithic RC construction using either ''strong'' (wet or dry) or "ductile" connections. A ''wet strong'' connection between precast members uses cast-in-place concrete or grout to fill the splicing closure. Precast structural systems with wet connections must then comply with all requirements applicable to monolithic RC constructions. A ''dry strong'' connection is a connection, not necessarily realized using cast-in situ concrete, that remains elastic while designated portions of structural members undergo inelastic deformations under the design actions (Bournas et al. 2013). Generally "dry strong" connections are achieved with use of dowels or anchor rods, threaded bolts, steel billets, steel plates, and steel angles. Many researchers have proposed dry connections with different configurations. These connection systems were found to behave as semi-rigid or rigid which primarily depend on dowel and shear key for force transfer from beam to column (Elliott et al. 2003). In ductile connections, the connection is designed for the required strength but with sufficient ductility to ensure non-brittle failure, normally achieved by using ductile threaded bolts, and steel plates.

The other main advantage of precast concrete structures which has not been fully explored is "*demountability*". It is possible to build a demountable building[1] using precast concrete frames with use of dry steel connections. Demountable building is a technical means to realize adaptable architecture. The demountable precast concrete system offers advantages with respect to saving of basic materials, energy and capital invested in the building when it comes to removal of these buildings at the end of their life cycle. Nevertheless, there is a limited amount of technical information regarding demountable structures in literature. In the Netherlands, some demountable systems were developed in the 90s' (Reinhardt 2012), which were classified as Mxb-5, CD-20, SMT, Bestcon-30 and Moducon-2000 systems. The existing demountable systems are not seismic resistant, cannot be demounted partially, and not easy to upgrade or replace. To the author's knowledge, there is limited research in the development of demountable precast system with use of strong rigid dry connection or ductile connection for seismic use. The present research is focused on development of sustainable and demountable precast RC frame building system using "strong" dry connections consisting of steel angle or steel tube, stiffened steel plates with pre-tensioned high strength friction grip (HSFG) bolts. Full details of the proposed system are explained in literature (Aninthaneni and Dhakal 2014). The proposed system can be demounted when/if needed and easily upgradable to meet increased design demand due to change of occupancy or change in design code, and in which damaged structural elements can be easily replaced after an earthquake.

In the proposed system, column to foundation connection can be designed as fixed or pin connection depending on strength and stiffness requirement. In a fixed base frame system, ground storey columns will be damaged along with beams in seismic events, and they have to be replaced after seismic events; whereas in a pin base connection only beams (which are easy to replace) will be damaged. The load path and desirable locations of plastic hinges in a frame with fixed and pin base under seismic force are shown in Figure 1a. The fixed base frame offers higher strength and stiffness compared to the pin base frame. However strength and stiffness of pin base frame can be considerably increased with increase of rebar percentage or increase of cross section sizes, which is qualitatively shown in Figure 1b. In this paper, several low to medium rise (3-6 storey) precast RC frame buildings with fixed and pin base are modelled and analyzed to understand the effect of pin base connection on the natural

[1] Demountable means always to disassemble a structure in such a way that the parts are not damaged and can be reused. It means usually to undo connections between structural parts

period of the frame as well as its lateral load resistance and stiffness. The reduction in lateral strength, initial lateral stiffness, and the reduction in demand due to longer period for various soil types are quantified. Finally, the possible options for increasing capacity and stiffness of pin base frame are then explained in detail.



(a) Fixed and pin base frame (b) Qualitative capacity curves

Figure 1. Seismic force resisting frame with fixed and pin base and qualitative capacity curves

ANALYTICAL METHOD

Pushover analyses of frames with fixed and pin bases are carried out using the nonlinear FE analysis software SAP 2000. Structural elements are modelled as elastic elements with lumped plasticity at ends (modelled as nonlinear rotational springs). A predefined lateral load pattern as per New Zealand seismic design standard is applied and increased until yielding in one member occurs. Thereafter the structure is modified with secant stiffness and lateral loads are increased further until the structure reaches its ultimate response. The nonlinear section properties for beams and columns are obtained from FEMA 356 guidelines which depend on the geometrical and mechanical properties of the member cross-section and the axial load.

PARAMETRIC STUDY

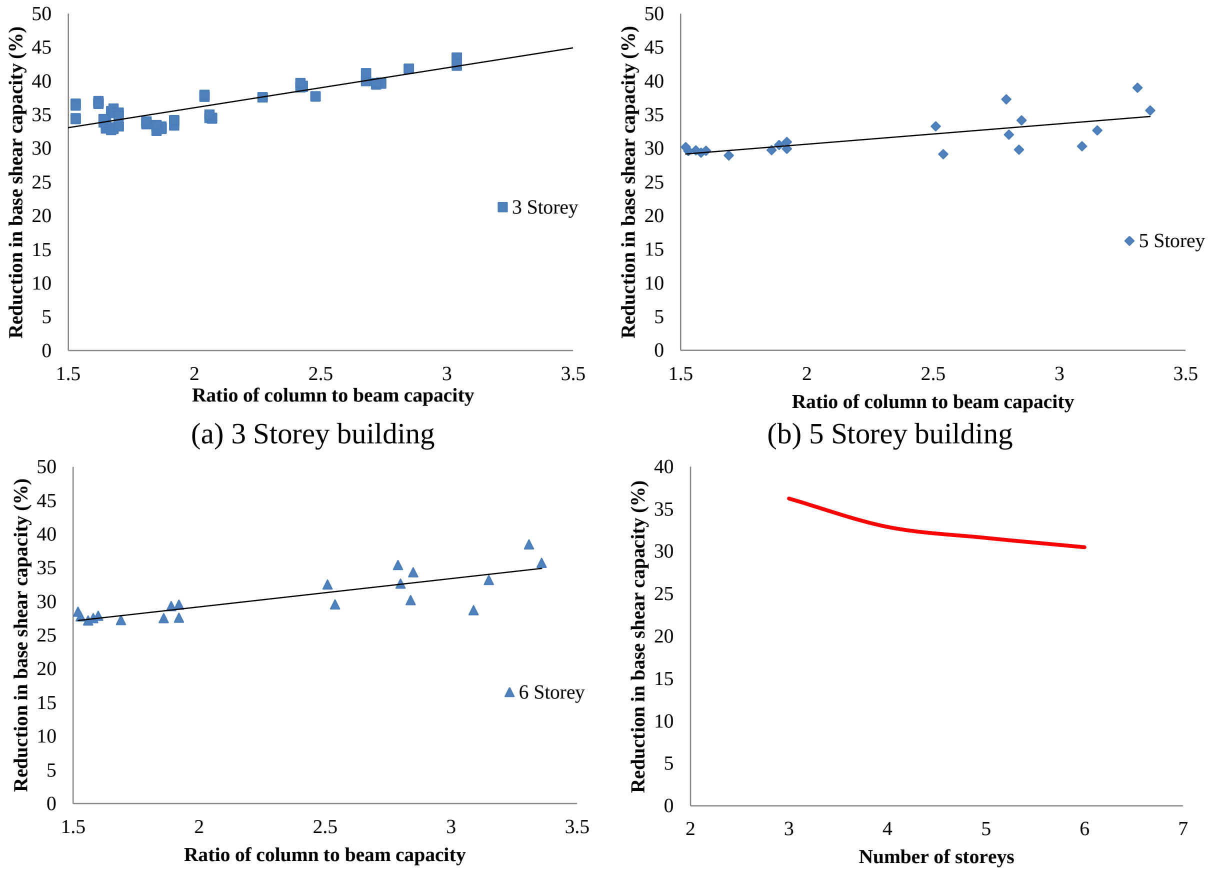
A frame with fixed base is chosen as the base structure, and is hereafter called the *reference frame*. In total, three hundred number of pushover analyses of the frames are performed with the varying the parameters mentioned in Table 1. For calculation of mass on the frame, it is assumed that structure considered in parametric study have 4 bays of 6m width in perpendicular to seismic force direction. Column to beam capacity ratio (β) is varied from 1.5 to 3.5 in the parametric study. Numerical results reported in the next section are used to explain the effect of base fixity on lateral strength and stiffness, natural period and demand.

Table1. Variables used in paramateric study for comparision of fixed and pin base frames.

Building characteristics		**Material description**		**Beam dimensions**	
No of storeys	3-6	Grade of concrete	35 N/mm^2	Dimensions	0.4x0.4-0.4x0.6 m
Storey height	3.6m	Grade of rebar	500 N/mm^2	Rebar percentage	0.38-0.92%
Span length	5-7m	**Loading details**		**Column dimensions**	
No of bays	3-5	Dead load	Roof: 4.75 kN/m^2 Other: 4.25 kN/m^2	Dimensions	0.4x0.5-0.4x0.6 m
Base boundary condition	Fix or pin	Live load	Roof: 2.5 kN/m^2 Other: 3.0 kN/m^2	Rebar percentage	0.8-3.44 %

RESULTS AND DISCUSSIONS

The reduction in base shear capacity of the pin base frame compared to the reference frame with varying number of storeys is shown in Figure 2d. It is observed that the reduction in average base shear capacity varies from 37% to 30% with increase in number of storeys from 3 to 6. The rate of reduction in base shear capacity with increase in number of storeys decreases mainly because of more beams in higher storey frames, the relative contribution of column fixity to the base shear capacity is less. It is observed that with increase of ratio of column to beam capacity, the base shear capacity reduces more, which is shown in Figures 2a-2c. This is due to the fact that the contribution of columns strength to the base shear capacity is limited in the pin base frame compared to the fixed base frame (in the pin base frame, main resistance to seismic forces comes from the beams flexural strength).

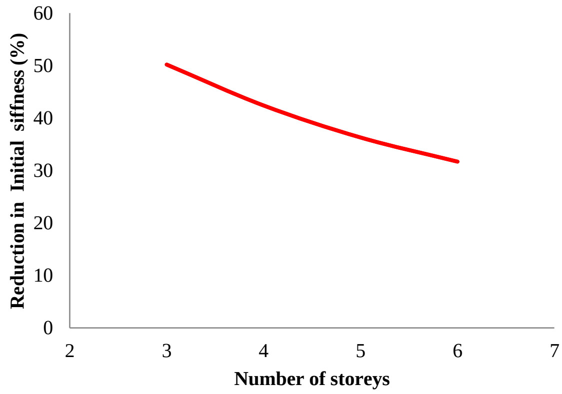


(a) 3 Storey building (b) 5 Storey building

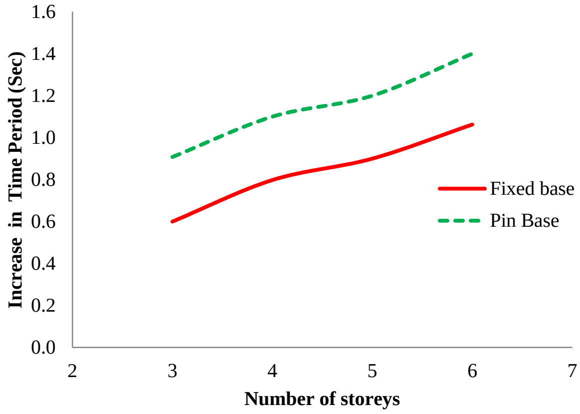
(c) 6 Storey building (d) Reduction in capacity vs storey number

Figure 2. Reduction in base shear capacity of pin base frame compared to fixed base frame

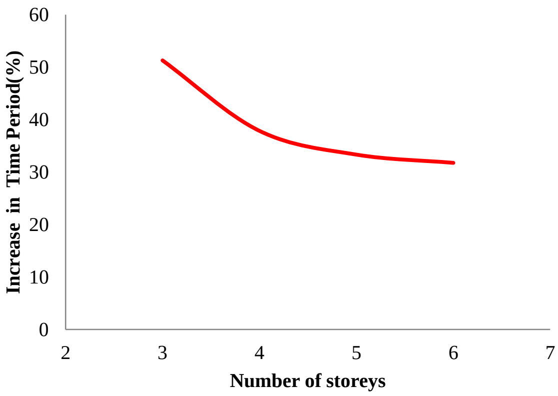
In the pin base frame, for low column to beam capacity ratio (i.e β <=2.25), it is highly likely to form storey mechanism, this is due to high column moment demand at the top of ground storey because of the pin base. The storey mechanism can be avoided by choosing β between 2.25 and 2.5 for 3 and 4 storey buildings and β between 2.75 and 3.0 for 5 and 6 storey buildings. Lack of rotational fixity at the column base (hinged condition) increases the lateral sway in the lower storeys than in higher storeys, and the overall response of the building is more of shear-type. On the other hand, full rotational fixity at the column bases restricts the lateral sway at the first storey and thus induces initial flexural behaviour near the base, but the overall response of the building is still of shear-type due to the flexural stiffness of the beams. The effect of base fixity (i.e. pin base) on lateral stiffness of building is considerably high. It is found from the parametric study that the reduction in average initial lateral stiffness varies from 50% to 30% with increase in number of storeys from 3 to 6, which is shown graphically in Figure 3a. Consequently the natural period of the pin base frame is higher than the fixed base frame by 50% to 30% depending on the number of storeys as shown in Figures 3b-3c and the seismic demand on the pin base frame will be less compared to the reference frame (i.e. fixed base frame). Figure 3d shows the reduction in demand compared to the fixed base frame for different soil conditions. It can be observed that the average demand reduces by 25% to 20% with an increase in number of storeys from 3 to 6.



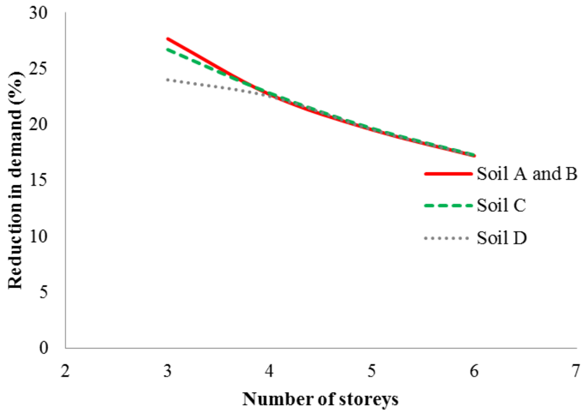
(a) Reduction in initial stiffness



(b) Increase in time period



(c) Increase in time period

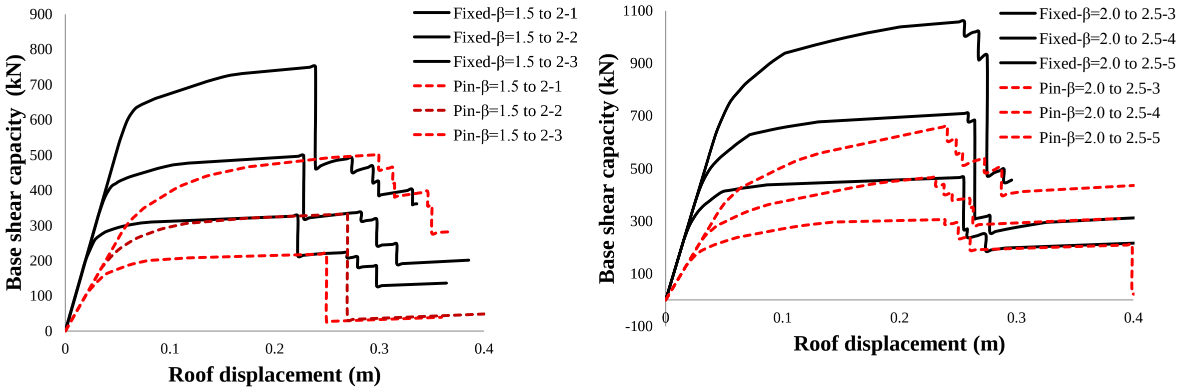


(d) Reduction in demand

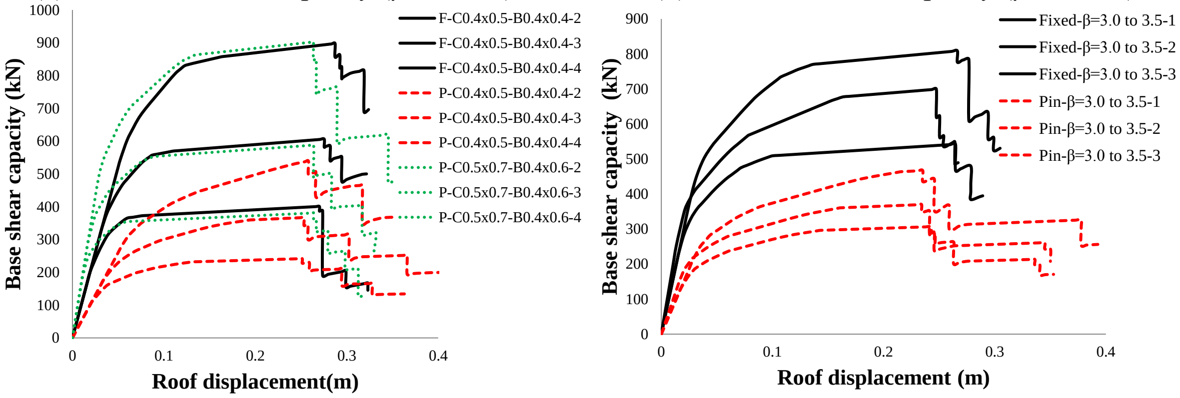
Figure 3. Variation of stiffness,time period & demand of pin base frame compared to fixed base frame

The capacity of the pin base frame can be increased without increasing the initial lateral stiffness by increasing the reinforcement ratio while keeping the cross section sizes unchanged. Comparison of capacity curves of 3 storey fixed and pin base frames with varying column to beam capacity ratio (β=1.5-3.5) is shown in Figure 4. Column to beam capacity ratio is varied by increasing the rebar percentage in beams and columns. In the figure "Fixed- β=1.5 to 2.0-1" indicates that the frame is fixed with column to beam capacity ratio between 1.5 and 2 and the number (1 to 5) indicates increasing rebar percentage both in beams and columns while keeping same cross section sizes. It is observed that to meet capacity of fixed base frame, the pin base frame requires higher percentage of rebar as shown in Figure 4. As explained earlier, for low β<=2.25, soft storey mechanism is likely to form in fixed and pin base frame, the sharp reduction in capacity indicates the governing mechanism is soft storey mechanism,which can be clearly observed in Figures 4a-4b. For high β>=3.0 values, it is not possible for the pin base frame to reach the capacity of the fixed base frame with higher rebar percentage as shown in Figure 4d, because the capacity of the pin base frame is limited by the capacity of the beams.

Both strength and stiffness of the pin base frame can be increased by increasing cross sectional dimensions and rebar percentage. Figure 4c shows the response of fixed base frames, pin base frames with the same cross sections and pin base frames with bigger cross sections. In the figure "F-C0.4x0.5-B0.4x0.4-2" indicates column dimensions are 0.4mx0.5m, beam dimensions are 0.4mx0.4m, and the final number (2 to 4) indicates increasing rebar percentage. It is observed that the strength and stiffness of pin base frame can be increased to the level of the reference frame (i.e. fixed base frame) by using bigger cross section sizes and more reinforcement.



(a) Column to beam capacity (β=1.5-2.0) (b) Column to beam capacity (β=2.0-2.5)



(c) Column to beam capacity (β=2.5-3.0) (d) Column to beam capacity (β=3.0-3.5)

Figure 4. Comparision of capacity of 3 storey fixed and pin base frame with varying β

CONCLUSIONS

This paper has investigated the effect of base fixity (fixed vs pin) in demountable precast reinforced concrete (RC) frame structural system. It is observed from numerical results presented herein that, in pin base (3-6 storey) frames the reduction in average base shear capacity is 37% to 30%, reduction in average initial lateral stiffness is 50% to 30%, increase in average time period is 50% to 30%, and the reduction in average demand is 25% to 20% compared to similar frames with fixed base. For low column to beam capacity ratio (i.e β<=2.25), pin base frames are likely to form soft storey mechanism, mainly due to high demand on ground storey because of pin base. The storey mechanism can be avoided by ensuring β (column to beam capacity ratio) greater than 2.25 for 3 and 4 storey buildings and 2.75 for 5 and 6 storey buildings. The reduction in capacity and stiffness of pin base frame can be recovered (if needed) by increasing the rebar percentage or the cross sectional dimensions or both. In conclusion, pin base connections in demountable precast frame buildings are definitely feasible, provided the β factor is properly chosen in design to avoid soft storey mechanism.

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