Evaluation of Seismic Behavior for Low-Rise RC Moment Resisting Frame with Masonry Infill Walls

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ABSTRACT:

Masonry infill walls are frequently used as interior partitions and exterior walls in low- or middle- rise RC buildings. In the design and assessment of buildings, the infill walls are usually treated as non-structural elements and they are ignored in analytical models because they are assumed to be beneficial to the structural responses. Therefore, their influences on the structural response are ignored. In case of buildings constructed in USA, high seismicity regions, infill walls have lower strength and stiffness than the boundary frames or they are separated from the boundary frames. Thus, previous assumptions may be reasonable. However, these systems are not usually employed in most of other countries. Therefore, the differences in seismic behaviors of RC buildings with/without masonry infill walls, which are ignored in structural design, need to be investigated. In previous studies, the infill walls have high lateral resistance and tend to partially separate from the boundary frames. And they form a compression strut mechanism as observed at a high lateral load level. In this study, structural analyses were performed for a masonry infilled low-rise RC moment-resisting frame. The infill walls were modeled as equivalent diagonal struts. And seismic behaviors of RC moment-resisting frame with/without masonry infill walls were evaluated.

From analytical results, masonry infill walls can increase the global strength and stiffness of a structure. Consequently, interstory drift ratio will be decreased but seismic forces applied to the structure were increased than design seismic load because natural period of the structure was decreased. And partial damage of infill walls by floor causes vertical irregularity of the strength and stiffness. The inelastic deformation of RC moment-resisting frame with soft story is concentrated on the first story columns and thus, partial damage may have possibility of collapse of system.

KEYWORDS: masonry infill wall, equivalent diagonal strut, nonlinear analysis, soft story, plastic hinge rotation angle

1. INTRODUCTION

Masonry infill walls are frequently used as interior partitions and exterior walls in low- or middle- rise RC buildings. In the design and assessment of buildings, the infill walls are usually treated as non-structural elements and they are ignored in analytical models because they are assumed to be beneficial to the structural responses. Therefore, their influences on the structural response are generally ignored. However, their stiffness and strength are not negligible, and they will interact with the boundary frame when the structure is subjected to ground motions. This interaction may or may not be beneficial to the performance of the structure, and it has been a topic of much debate in the last few decades(Mehrabi and Shing, 2002).

In case of buildings constructed in USA, high seismicity regions, infill walls have lower strength and stiffness than the boundary frames or they are separated from the boundary frames. Thus, previous assumptions may be reasonable. However, these systems are not usually employed in most of other countries. In recent earthquakes, numerous buildings were severely damaged or collapsed due to the presence of non-structural masonry partitions which was not included in structural design. Figure 1(a) shows the damage to infill walls and Fig. 1(b) shows collapse of lower stories when Izmit earthquake in Turkey.

(a) Damage to masonry infill walls (b) Failure of building frame with masonry infill

Figure 1 Damage of moment resisting frame building

In case of residential buildings constructed in Korea, many buildings have pilotis in lower stories to meet the architectural needs as shown in Fig. 2. Infill walls can over-strengthen the upper stories resulting in a soft first story to the structure, which is very weak from the earthquake resistance. In the design of the buildings, the infill walls of upper stories are usually considered as non-structural elements and they are not included in the analytical model. Therefore, the differences in seismic behaviors of RC buildings with and without masonry infill walls, which are usually ignored in structural design, are required to be investigated. In previous studies(Mehrabi and Shing, 2002), it has been found that the infill walls have high lateral resistance and tend to partially separate from the boundary frames. And they form a compression strut mechanism as observed at a high lateral load level.

In this study, structural analyses were performed for masonry infilled low-rise RC moment-resisting frames. The infill walls were modeled as equivalent diagonal struts. And seismic behaviors of RC moment-resisting frame with and without masonry infill walls were evaluated.

Figure 2 Villa-style house buildings with pilotis in lower story

2. INFLUENCE OF MASONRY INFILL WALLS ON STRUCTURAL SEISMIC RESPONSE

It may be not adequate to assume that masonry infill walls are always beneficial to the structural response. And the influence of infill walls for seismic response of building structures may be positive or negative, depending on a series of parameters as, for example, relative stiffness and strength between the frames and the masonry walls. Even if they are relatively weak, masonry infill walls can change the structural response, attracting forces to a part of the structure that have not been designed to resist them(Mehrabi and Shing, 2002).

2.1. Behavior of masonry infilled frames by lateral loads

The behavior of masonry infilled frame is influenced by the interaction of the infill with its boundary frame. The lateral resistance of masonry infilled frame is not equal to a simple sum of those of the infill and the boundary frame because frame–infill interaction can alter the load resisting mechanisms of the individual components. At a low lateral load level, a masonry infilled frame acts as a monolithic load resisting system. As the load increases, the infill tends to partially separate from the boundary frame and form a compression strut mechanism as observed in many early studies(Mehrabi and Shing, 2002). However, the compression strut may or may not evolve into a primary load resistance mechanism of the structure, depending on the strength and stiffness properties of the infill with respect to those of the boundary frame.

2.2. Analytical model of masonry infill walls

The models for masonry infill walls can be classified as micro and macro models. In the micro model, infill walls are modeled in detail at components level such as mortar, bricks, and interface elements, to represent the behavior of infill walls more accurately. However, significant calculation effort and a large amount of parameters have to be calibrated. They may be useful for local analysis, but impractical for the global analysis of a building.

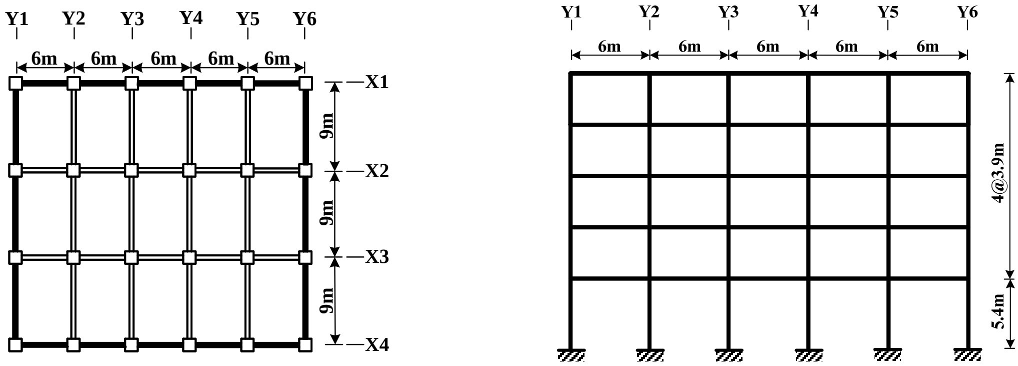
The macro model allows the representation of the global behavior of infill walls and its influence in the structural response. The most commonly used macro-model is the bi-equivalent diagonal strut model. In this study, the masonry infill walls were modeled by using a macro model.

3. EXAMPLE STRUCTURES

3.1. Design of example structures

Example structures used in this study are 5-story reinforced concrete framed structures. Example structures have the plan as shown in Fig. 3(a) and the elevation of example structures are illustrated in Fig. 3(b). Example structures were designed with dead loads and live loads of 5.5kN/m^2 and 2.5kN/m^2, respectively. Wind loads and seismic loads are determined according to UBC-97. The basic wind speed of 70 mph was assumed to determine wind loads.

The soil profile type was assumed to be S_B and the importance factor of 1.0 was used to determine seismic loads. Example structures with 5-stories are designed for seismic zones 1, 2B and 4 to investigate inelastic responses of building in low, moderate and high seismicity regions(LSR, MSR, and HSR).

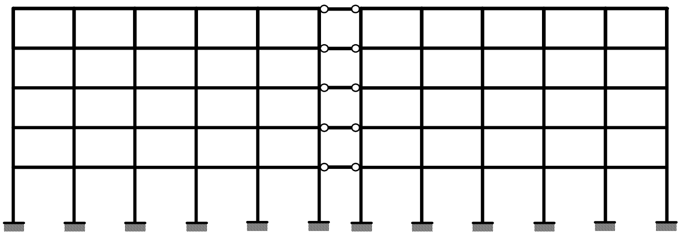


(a) Plan (b) Elevation of the 5-story building

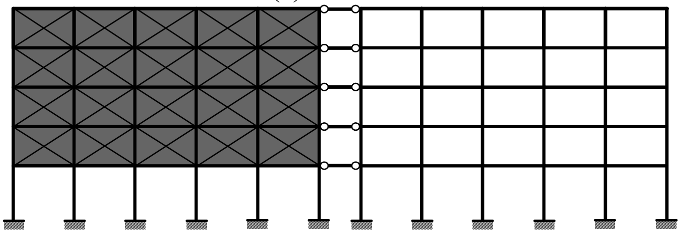
Figure 3 Plan and elevation of the example building structures

3.2. Analytical model of example structures

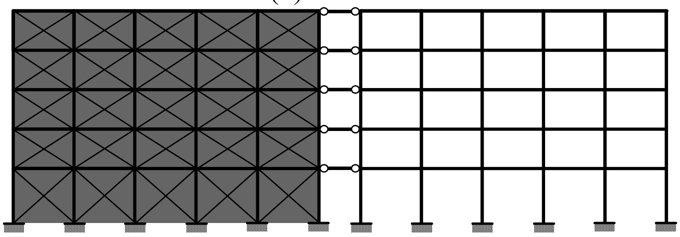
The computer code DRAIN-2DX was employed for 2-dimensional nonlinear analysis of example structures. Therefore, 3-dimensional example structures are replaced by equivalent 2-dimensional frames, connected outside frame and interior frame by rigid body elements as shown in Fig. 4. Three types of structural system with the same frame with different allocation of infill walls are used to evaluate the influence of masonry infill walls on seismic behavior of RC moment-resisting frames. F Model without diagonal struts, S Model with diagonal struts except in the first story and W Model with diagonal struts all stories in Fig. 4.



(a) F Model



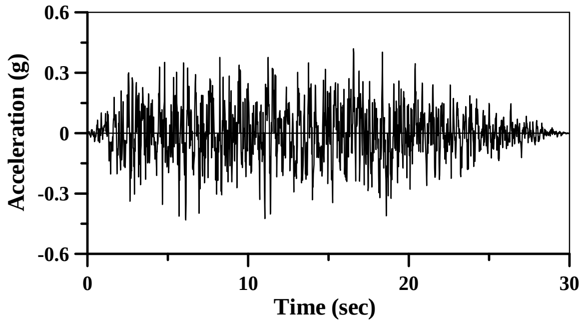
(b) S Model



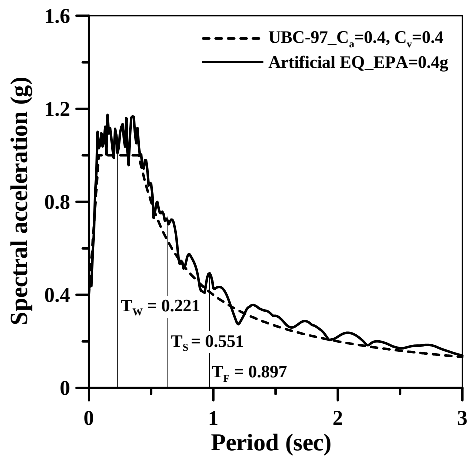
(c) W Model

Figure 4 Analysis model of the example building structures

Dynamic analyses of example structures were performed using artificial earthquake, which was created to the design spectrum, scaled to have the effective peak ground acceleration(EPA) of 0.08g, 0.2g and 0.4g as ground motion. Figure 5 shows acceleration time history and spectral acceleration of artificial earthquake.



(a) Acceleration time history



(b) Spectral acceleration

Figure 5 Artificial earthquake (EPA=0.4g)

For the estimation of the initial stiffness and maximum strength of the infill walls, the effective width W_{ef} , initial stiffness K_{in} and maximum strength F_{max} proposed by Matjaž & Peter(2002) were adapted.

$$W_{ef} = 0.175(\lambda_h H)^{-0.4}\sqrt{H^2+L^2}\,,\quad \lambda_h = \sqrt[4]{\frac{E_w t_w \sin(2\theta)}{4E_c I_c H_{in}}} \tag{3.1}$$

where E_w and E_c are the modulus of elasticity of the infill wall and the concrete (i.e. the frame material), respectively. And, θ=arctan(H/L) is the inclination of the diagonal, t_w is the thickness of the infill wall, and I_c is moment of inertia of the column of the frame, whereas H_{in}, H and L are the net height of the infill wall but the storey height, and the bay length of the frame. The initial lateral stiffness K_{in} is equal to

$$K_{in} = \frac{E_w W_{ef} t_w}{\sqrt{H^2 + L^2}} \cos^2 \theta \tag{3.2}$$

A simplified form of the maximum strength of infill walls(Matjaž and Peter, 2002) is

$$F_{\max} = 0.818 \frac{L_{in} t_w f_{tp}}{C_I} \left(1 + \sqrt{C_I^2 + 1}\right), \quad C_I = 1.925 \frac{L_{in}}{H_{in}} \tag{3.3}$$

where f_{tp} is the cracking strength of the infill, obtained from a diagonal compression test, L_{in} and H_{in} are the length and the height of the infill.

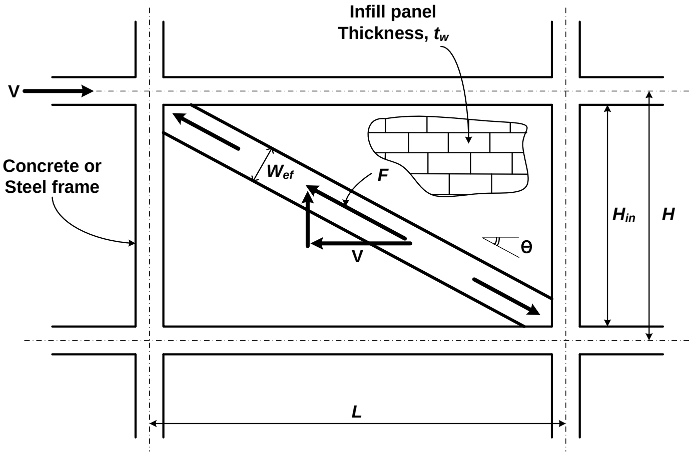


Figure 6 Equivalent diagonal strut model (FEMA-306, 1998; NZSEE, 2006)

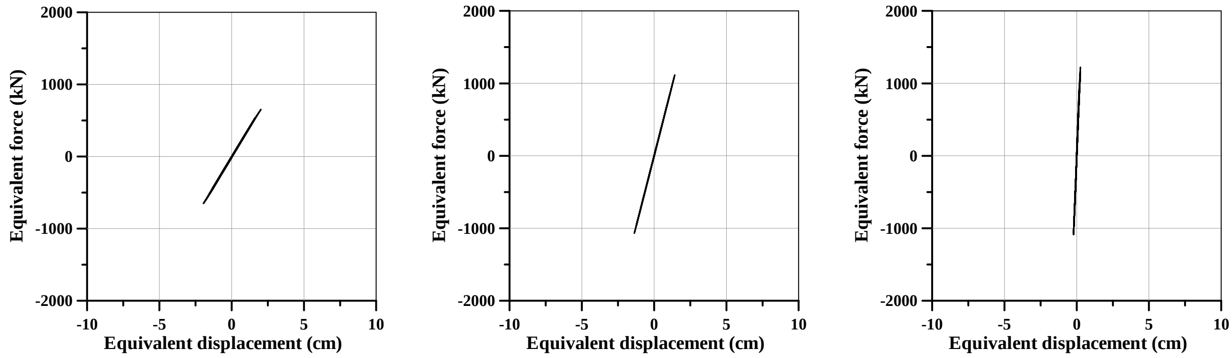
The value of the initial stiffness can be obtained using the Eqs. (3.1) ~ (3.2) by assuming values of 1.2 and 24 kN/mm^2 for the modulus of elasticity of masonry infill and of concrete, respectively. Furthermore, the value of the maximum strength can be obtained using the Eq. (3.3), assuming a value of 0.36 N/mm^2 for the cracking strength of infill.

The cracking forces for infill walls were assumed to be equal to approximately half of the corresponding ultimate forces. The cracking and maximum displacements in the horizontal direction are about 0.5 and 1.5% of the storey height(NZSEE, 2006).

4. EVALUATION OF SEISMIC BEHAVIOR BY NONLINEAR TIME HISTORY ANALYSIS

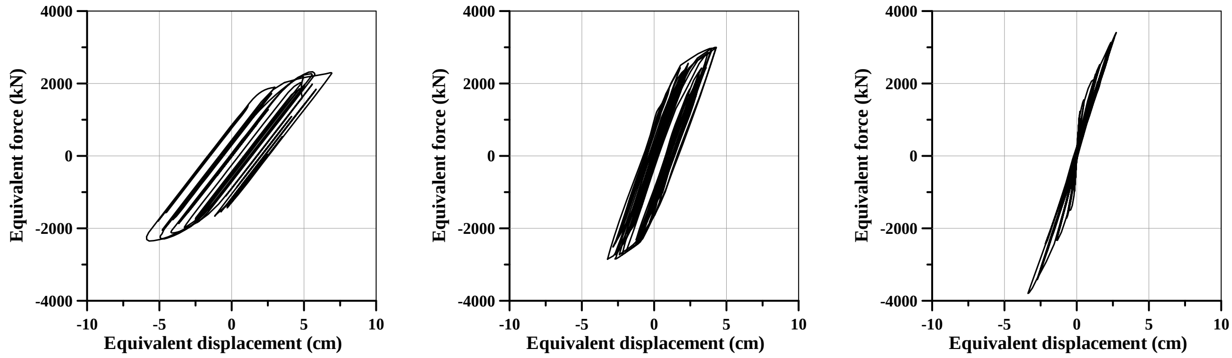
The force-displacement relationship is not easy to define this relationship for MDOF structures. Roof displacement and base shear are used in ATC-40 to obtain force-displacement relationship for MDOF structures. However, the method proposed by Lee(Lee, Song and Yun, 1996) was employed in this study because it can account for the deformed shape of structures.

Force-displacement relationships of SMRF in low and high seismicity regions are shown in Figs. 7, 8. Structures in low and high seismicity regions were designed with the same response modification factor of 8.5. However, structures in low seismicity regions has larger overstrength factor than those in high seismicity regions because the design may be governed by gravity loads. Inelastic deformation of S and W Model in low seismicity regions, which subjected to ground motions of design level, are significantly small because masonry infill walls can increase the global strength and stiffness of a structure.



(a) F Model (b) S Model (c) W Model

Figure 7 Force displacement relationships of SMRF in LSR; Artificial EQ EPA=0.08g



(a) F Model (b) S Model (c) W Model

Figure 8 Force displacement relationships of SMRF in HSR; Artificial EQ EPA=0.4g

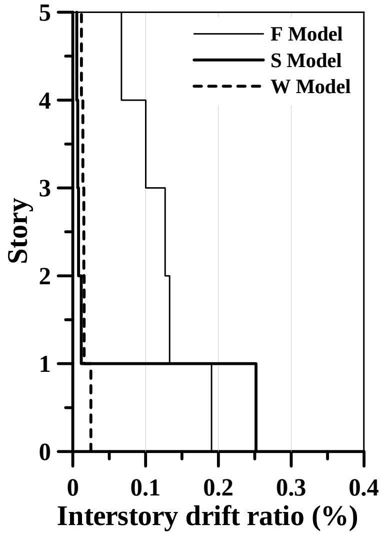
Figure 8 shows that stiffness of W Model in high seismicity regions are decreased because stiffness of masonry infill walls is decreased by cracking of walls in analysis time. The responses of S Model in high seismicity regions are concentrated on the first story because masonry infill walls can over-strengthen the upper stories of a structure. It is similar to the responses of F Model in high seismicity regions.

Seismic responses of example structures for three levels of seismic hazard were evaluated and inter-story drift ratios are shown in Fig. 9. Inter-story drifts of S Model were similar to those of W Model except the first story where they far exceed those of F Model. Therefore, structures with infill walls in all stories except in the first story may be subjected to significant earthquake damage if they are designed without proper consideration of infill walls. Irregular distribution of masonry infill walls can over-strengthen the upper stories of a structure and very weak against the earthquake resistance. The damage is concentrated on the first story columns and thus, partial damage may have possibility of collapse of system.

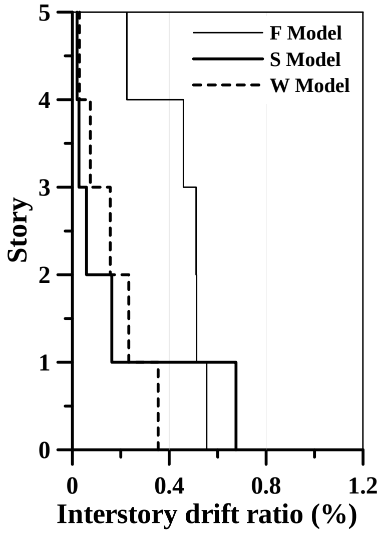
Because infill walls resisted most of lateral loads, boundary frames of structures in low seismicity regions resisted to low lateral loads. And boundary frames of structures in high seismicity regions resisted to high lateral loads by crack of walls. But the concentrated response on the first story of structures in low seismicity regions is larger than those in high seismicity regions.

Table 1 Maximum inter-story drift ratio (unit: %)

	F Model	S Model	W Model
LSR	0.19	0.25	0.02
HSR	0.55	0.68	0.35



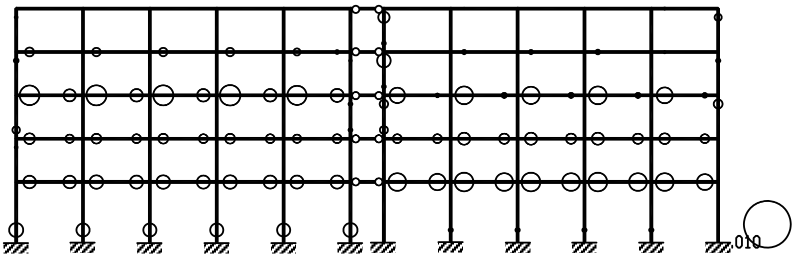
(a) LSR



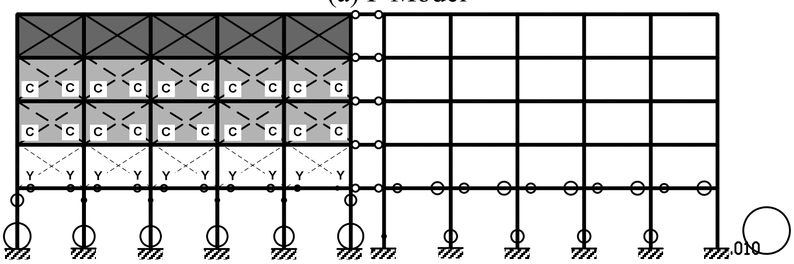
(b) HSR

Figure 9 Inter-story drift ratio of SMRF building

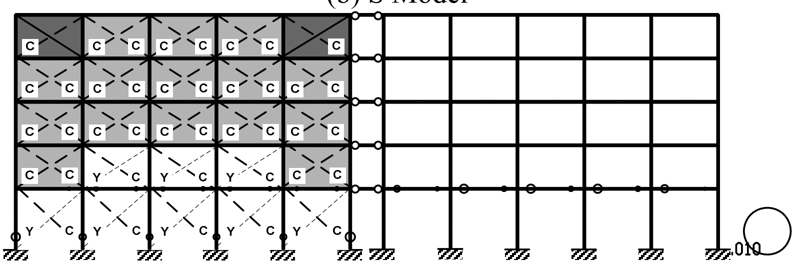
Figure 10 shows the distribution of plastic hinges in example structures. The size of circle indicates the plastic hinge rotation. In these figures, infill walls in dark gray are undamaged, walls in light gray are cracked and walls in white are damaged. Plastic hinges in S Model with soft story were concentrated on the first story compare to those of F Model as shown in these figures. The damage is concentrated on the first story columns



(a) F Model



(b) S Model



(c) W Model

Figure 10 The distribution of plastic hinges of SMRF in HSR

5. CONCLUSIONS

In this study, nonlinear time history analyses were performed for a masonry infilled low-rise RC moment-resisting frame. The infill walls were modeled as equivalent diagonal struts. And seismic behaviors of RC moment-resisting frame with and without masonry infill walls were investigated. Some of the main conclusions are as follows:

1) The increased the global stiffness of the structure by the masonry infill walls will result in shorter natural period and increase seismic forces.

2) The inelastic deformation of structures in low seismicity regions is significantly smaller than those in high seismicity regions because over-strength of structures is increased by strength of masonry infill walls.

3) Inter-story drifts of S Model were similar to those of W Model except the first story where they far exceed those of F Model.

4) Therefore, structures with infill walls in all stories except in the first story may be subjected to significant earthquake damage if they are designed without proper consideration of infill walls.

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