패널 영역의 주기거동에 대한 모델링

Modelling for Cyclic Behavior of the Panel Zone

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요 약 : 본 논문은 단조하중(monotonic loading)하의 강재 보-기둥의 절점의 패널 영역 거동을 연구한 논문(Kim 1997)의 후속 논문으로 주기하중에 대한 패널영역의 거동을 해석하기 위한 이력법칙(hysteretic rules)에 관한 것이다. 제안된 이력법칙은 실험결과와 합당한 상관관계를 보여주었고, 이 이력법칙을 사용한 패널영역요소의 해석결과가 실험결과와 잘 일치하는 것으로 나타났다. 한편 보강판(a doubler plate)을 갖는 패널영역에 대한 해석과 실험결과로 부터 보강판이 패널영역전달력(panel zone shear force)을 저항하는데 있어 부분적인 효과만 있다는 것을 알 수 있었다. 제안된 패널영역요소는 구조물의 전체 거동과 국부 변형을 기존의 패널영역요소(bilinear panel zone element)보다 정확하게 예측 할 수 있었다.

핵 심 용 어 : 패널 영역, 지진 거동, 주기 하중, 보강판, 해석 모델

1. Introduction

In a companion paper (Kim 1997), the results of an analytical study on the panel zone behavior of the bare steel beam-to-column joints under monotonic loadings have been presented. All the definitions used in the companion paper are retained, and the equations of that part are referred to in this paper. This paper documents hysteretic rules for the cyclic load-deformation response of the panel zone region at the bare steel beam-to-column joint, which are required for the analytical element presented in the companion paper. Panel zone stiffness and strength can be increased by the attachment of web doubler plates to the column within the joint region. The effectiveness of a doubler plate in resisting the panel zone shear force is also investigated in this paper.

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A couple of hysteretic models have been developed to describe the cyclic behavior of panel zones. The first model is based on bilinear kinematic hardening, and has been mostly used in the dynamic analysis of moment resisting frames. The second model, which was developed by Wang (1988), is based on a multi-linear hardening rule. This model shows better correlation with test data than the bilinear model.

Figure 1 shows a comparison of the bilinear model and test data for the panel zone of Krawinkler specimen A1. The existing bilinear panel model shows poor performance. The model underestimates the strength by about 80 percent. The overall subassemblage displacement obtained by the bilinear panel zone model and the beam-column element developed by Kim (1995) is compared with the experimental response in Fig. 2. The figure shows that the analytical results underestimate the strength of the test subassemblage as in Fig. 1. From this discussion it can be concluded that the behavior of the panel zone can play an important role in the overall responses of moment resisting frames and a realistic model for the panel zone is needed.

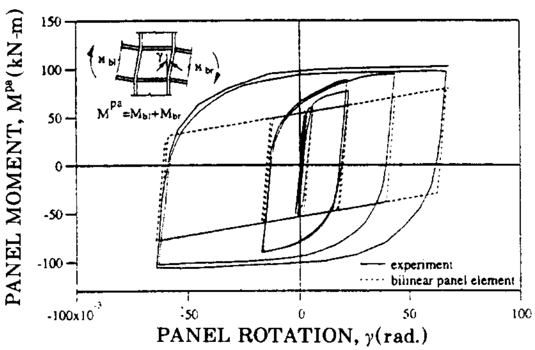


Fig. 1 Comparison of Test Results and the Existing Bilinear Panel Model for the Panel Zone of Krawinkler Specimen A1(Krawinkler 1971)

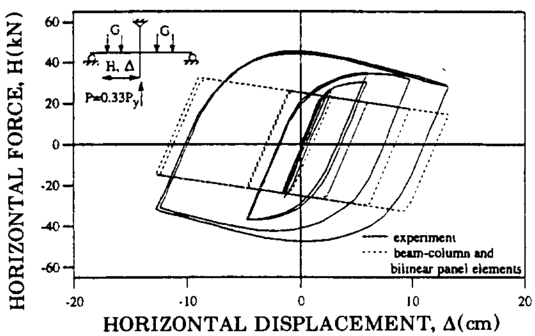


Fig. 2 Comparison of Test and the Analysis Using the Bilinear Panel Model for Overall Response for Krawinkler Specimen A1(Krawinkler 1971)

2. Hysteretic Rules for Cyclic Behavior of Panel Zones

In this study, hysteretic rules for the panel zone are developed based on Dafalias' bounding theory (Dafalias 1975). This model also uses Cofie's rules for the movement of the bound line (Cofie 1988). Based on observations from experiments and FEM analyses for panel zones, it has been found that for large plastic rotations, the shear strains in the panel zone are distributed nearly uniformly within the panel, and the value of joint rotation is close to the value of the average shear strain in the panel (Krawinkler 1971 and Wang 1988). Therefore, it is assumed that the panel zone moment-rotation relationships can be determined from the material properties of the panel zone using Cofie's rules. These rules for the movement of the bound line, which were developed for stress-strain relationships, will be adopted for the panel zone moment-rotation relationships.

The main feature of Cofie's model is that the cyclic steady state curve is used to describe the movement of bounding line. In this study, the same kind of cyclic steady state curve is developed to describe the movement of the bounding line for the cyclic behavior of panel zones, as follows:

$$\frac{\gamma}{\gamma_n} = \frac{M^{pa}}{M_n^{pa}} + \left(\frac{M^{pa}}{0.85 \cdot M_n^{pa}}\right)^c \tag{1}$$

where M_n^{pa} and γ_n are the normalizing panel moment and corresponding elastic rotation, respectively. By comparison with available cyclic test data, it has been empirically found that the constant C of the cyclic steady state curve is 4.2 to 4.4.

Experimental and FEM results suggest that column flanges do not significantly influence panel zone stiffness during cyclic loading, but do have a significant effect on panel zone strength. From FEM results for joints with the same dimensions except column flange thickness, it has been found that the effect of column flange thickness on the strength of the joint during cyclic loading can be normalized by M_n^{pa} (Wang 1988).

$$M_n^{pa} = M_y^{pa} + 2M_{pcf} \tag{2}$$

where M_{pcf} is the plastic moment of column flange. The elastic rotation corresponding to the normalizing moment M_n^{pa} is

$$\gamma_n = \frac{M_n^{pa}}{K_e} \tag{3}$$

To describe the inelastic behavior of the joint during cyclic loading the shape factor is employed, which was first used for cyclic stress-strain relationships by Dafalias (1975). The procedure for obtaining the shape factor $\hat{h}$ is as follows:

i) Choose the point A such that $0.1 \leq \delta_A / \delta_{in} \leq 0.5$, as shown in Fig. 3.

ii) Calculate the shape factor from

$$h = \delta_A/\gamma_p^A + \left(\delta_{in}/\ \gamma_p^A\right) \cdot \left[\ ln(\delta_{in}/\ \delta_A) - 1\right]$$

iii) Normalize the shape factor by the plastic stiffness of the bound line

$$\hat{h} = h/K_p^{bl}$$

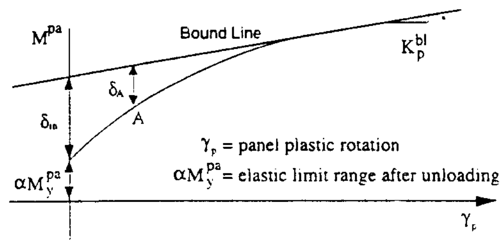


Fig. 3 Shape Factor for Inelastic Behavior

It has been determined that a shape factor $\hat{h}$ of 20 for the inelastic curves of panel zones, as shown in Fig. 4a, provides a good correlation with experimental data. It has been also found that an elastic limit factor α of 1.4 and a plastic stiffness of the bound line of $K_p^{bl} = 0.008K_e$ provide good correlation with experimental data. The position of the initial bound line is determined by drawing the line with the slope of the bound line at the point with the corresponding slope on the cyclic steady state curve and making the resulting line intersect the moment axis. The plastic stiffness K_p^A at the point A as shown in Fig. 3 is calculated by using the shape factor $\hat{h}$ and the plastic stiffness of the bound line K_p^{bl}, as follows:

$$K_p^A = K_p^{bl}\left[1+\hat{h}\frac{\delta_A}{\delta_{in}-\delta_A}\right] \tag{4}$$

The corresponding tangent stiffness K_t^A is determined by using the elastic stiffness K_e and the plastic stiffness K_p^A.

$$K_t^A = \frac{K_e \cdot K_p^A}{K_e + K_p^A} \tag{5}$$

The bounding line is updated whenever load reversals occur. The procedure for shifting the bounding line is presented below.

i) Whenever unloading occurs, the mean values and the amplitude for the last half cycle of loading history, as shown in Fig. 4b, are calculated.

$$M_m^{pa} = 0.5(M_A^{pa} + M_B^{pa}) \tag{6a}$$

$$\gamma_m^{pa} = 0.5(\gamma_A^{pa} + \gamma_B^{pa}) \tag{6b}$$

$$M_a^{pa} = 0.5\left|M_A^{pa} - M_B^{pa}\right| \tag{7a}$$

$$\gamma_a^{pa} = 0.5\left|\gamma_A^{pa} - \gamma_B^{pa}\right| \tag{7b}$$

where the subscripts 'm' and 'a' stand for a mean value and an amplitude, respectively.

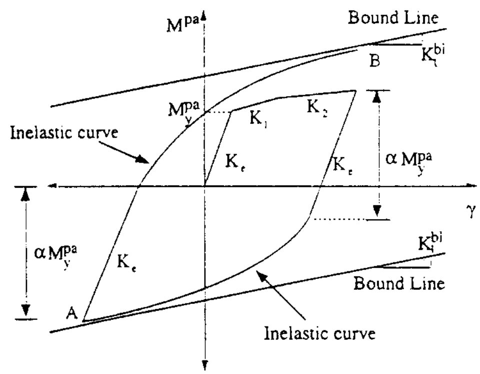
ii) Calculate the difference between the moment amplitude M_a^{pa} and the moment M_s^{pa} on the cyclic steady curve corresponding to the rotation amplitude, γ_a^{pa}

$$\Delta M^{pa} = M_s^{pa} - M_a^{pa} \tag{8}$$

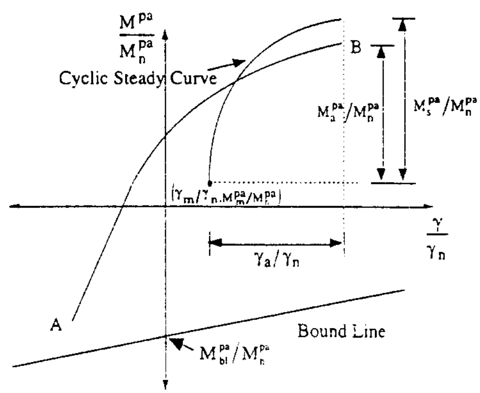
iii) If $\Delta M^{pa} > 0$, cyclic hardening is predicted to take place in the next excursion. Update the bound by moving it outward by an amount equal to $2F_H(\Delta M^{pa}/M_n^{pa})$, where F_H is the hardening factor.

$$\left(\frac{M_{bl}^{pa}}{M_n^{pa}}\right)_{new} = \left(\frac{M_{bl}^{pa}}{M_n^{pa}}\right)_{old} - 2F_H\left(\frac{\Delta M^{pa}}{M_n^{pa}}\right) \tag{9}$$

iv) If $\Delta M^{pa} < 0$, cyclic softening is predicted to take place in the next excursion. Update the



(a) Elastic Limit Range After Unloading



(b) Movement of Bound Line

Fig. 4 Hysteretic Rules for Panel Zones

bound by moving it inward by an amount equal to $2F_s(\Delta M^{pa}/M_n^{pa})$, where F_s is the softening factor.

$$\left(\frac{M_{bl}^{pa}}{M_n^{pa}}\right)_{new} = \left(\frac{M_{bl}^{pa}}{M_n^{pa}}\right)_{old} - 2F_S\left(\frac{\Delta M^{pa}}{M_n^{pa}}\right) \tag{10}$$

v) Further move the bound by an amount equal to $F_R M_m^{pa}$, where F_R is the mean value relaxation factor.

$$\left(\frac{M_{bl}^{pa}}{M_n^{pa}}\right)_{new} = \left(\frac{M_{bl}^{pa}}{M_n^{pa}}\right)_{new} - F_R M_m^{pa} \tag{11}$$

The same values used in Cofie's study, $F_H=0.45$, $F_s=0.07$, and $F_R=0.05$, are adopted in the proposed model.

3. Comparison with Experimental Results

The developed panel zone hysteretic rules are compared with test results for nine specimens tested by Krawinkler (1971), Slutter (1981), and Popov (1985).

A vertical stiffener plate is attached approximately at mid-width of the panel zone in Popov specimens 6 and 8. This is intended to represent a connection plate for a floor beam framing in from the perpendicular direction. In the analyses of Popov specimens 6 and 8, the vertical stiffener is not considered under the assumption that the resistance of these stiffeners to the panel zone shear forces is negligible.

Continuity plates are used to transfer beam flange forces to the column web in the specimens, except in Krawinkler specimen B and Popov specimen 3. If no continuity plates are required, the flange forces are assumed to be directly transferred to the column web. This detail can be used only if the column flanges are sufficiently thick. From comparison of test results for specimens with and without continuity plates, it has been reported by Popov (1985) that as far as the stiffness and strength of the panel zone were concerned, the test results showed little difference. Even though the monotonic and cyclic response rules for the panel zone are calibrated to test specimens with continuity plates, no modification is attempted to account for the behavior of panel zones without continuity plates under the above observation and the assumption that the validity of the panel zone tests is not dependent on the use of continuity plates.

For some specimens a doubler plate is used to increase the capacity of the panel zone. Test results (Becker 1971) showed that for every load level, except maximum load, the strain in the doubler plate was significantly less than that in the column web. Thus, the doubler plates were not fully effective. To account for the limited participation of a doubler plate in resisting panel shear, a reduction factor was considered in calculating the yield moments and stiffnesses of the panel zone with a doubler plate (see Eq. 13b in the companion paper). The effectiveness of doubler plates is affected by the method used to connect them to the column (one side attachment, both sides attachment, welding details, etc.). In this paper the case that a doubler plate is attached to only one side of the panel zone is studied.

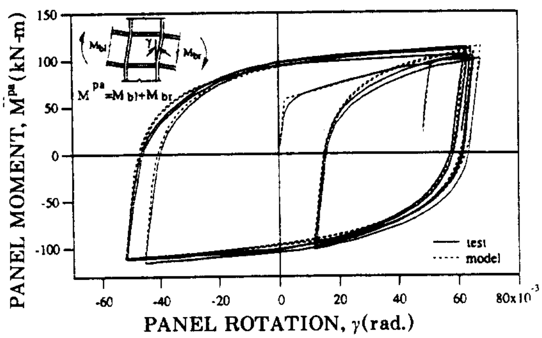


Fig. 5 Comparison of the Hysteretic Rules and Test Data for Krawinkler Specimen A2(Krawinkler 1971)

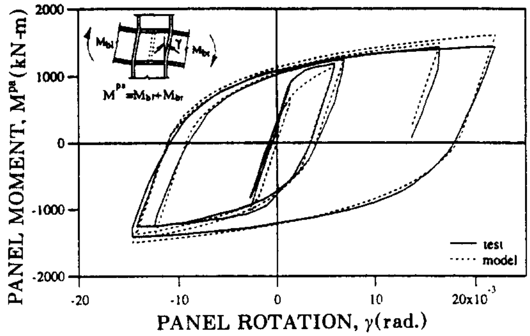


Fig. 8 Comparison of the Hysteretic Rules and Test Data for Popov Specimen 6(Popov 1985)

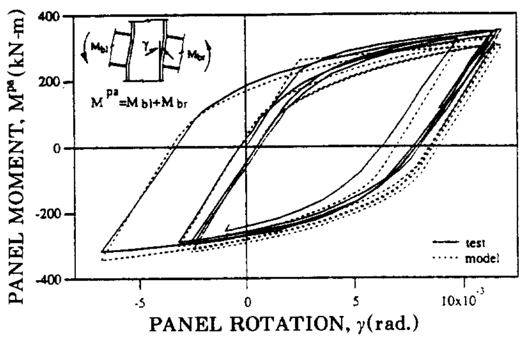


Fig. 6 Comparison of the Hysteretic Rules and Test Data for Krawinkler Specimen B2(Krawinkler 1971)

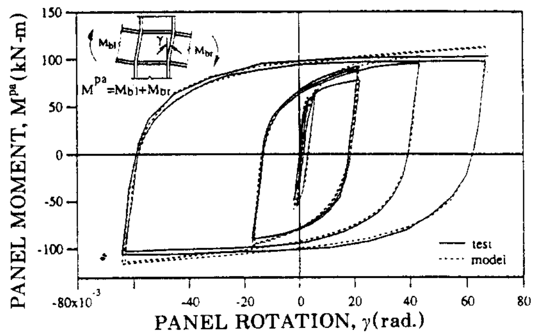


Fig. 9 Comprison of the Hysteretic Rules and Test Data for Krawinkler Specimen A1(Krawinkler 1971)

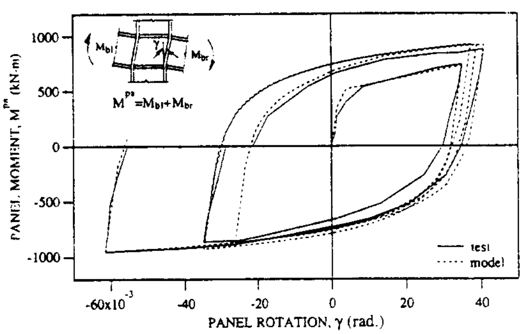


Fig. 7 Comparison of the Hysteretic Rules and Test Data for Slutter Specimen 1(Slutter 1981)

Figures 5 to 9 show the comparison of the analytical response obtained by the hysteretic rules and test results for the panel zones with no doubler plate. In Figs. 8 and 9, the test results for Popov specimen 6 and Krawinkler specimen A1 are plotted against the predictions made by the developed model. The match is good for the cycles in which large deformations are imposed. For the first few cycles in which small deformations are imposed, the predictions are not as good. For Krawinkler specimens A2 and B2 and Slutter specimen 1 (Figs. 5 to 7), a large strain amplitude is applied for the first half cycle, causing large plastic deformation (far beyond the onset of strain hardening) in the panel zone. The model seems to work better for a large strain amplitude for which strain hardening effects are fully developed than for a small strain amplitude. The developed model has been applied to five specimens with no doubler plate. In spite of the simplicity of the model, reasonable agreement has been established between model predictions and test results.

In Figs. 10 to 12, the analytical results are compared with test results for specimens with doubler plates. In these specimens, the yield stress of the doubler plates is approximately the same as that of the column web. In the analyses, the reduction factor of $R_f=0.4$ was applied to account for strain incompatibility between the column web and the doubler plate. For the small strain amplitude cycles, the difference between the model predictions and experimental responses can be explained by the same reason as in the discussions for the specimens with no doubler plate. The doubler plate apparently provides little increase in panel zone stiffness at low loads. In general, the analytical results obtained by using the reduction factor of $R_f=0.4$ show fair agreement with test results in spite of the complexity of the problem.

Figure 13 shows the comparison of the analytical and experimental results for Popov specimen 8, for which the yield stress ($\sigma_y=49$ ksi) of the doubler plate is different from that ($\sigma_y=60$ ksi) of the column web by about 18%. Since the yield stress of the doubler plate is

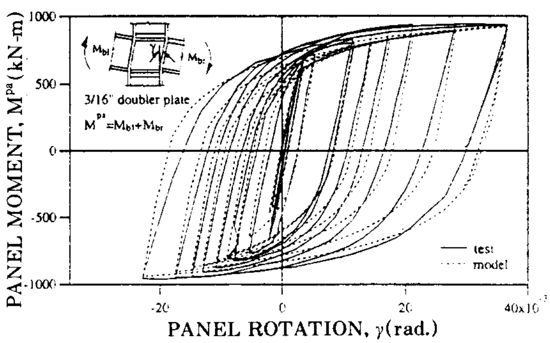


Fig. 10 Comparison of the Hysteretic Rules and Test Data for Popov Specimen 2(Popov 1985)

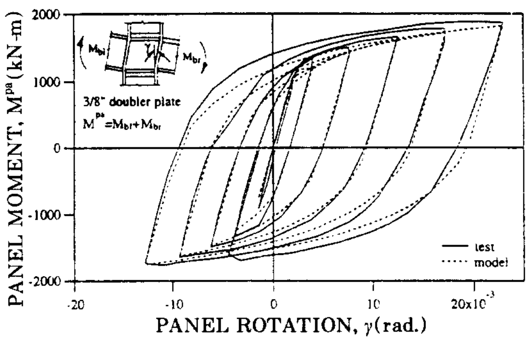


Fig. 12 Comparison of the Hysteretic Rules and Test Data for Popov Specimen 4(Popov 1985)

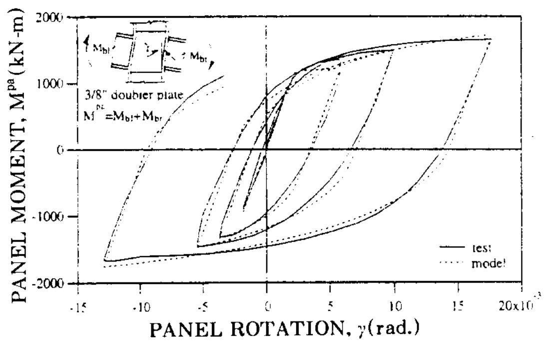


Fig. 11 Comparison of the Hysteretic Rules and Test Data for Popov Specimen 3(Popov 1985)

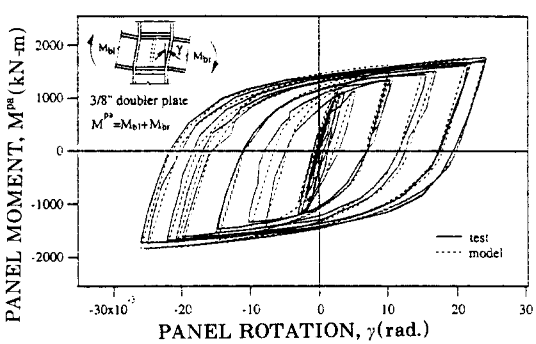


Fig. 13 Comparison of the Hysteretic Rules and Test Data for Popov Specimen 8(Popov 1985)

much different from that of the column web, two panel elements are employed in parallel to obtain the analytical results. To obtain better correlation between the analytical results and the test data, the reduction factor of $R_f=0.1$ was used. When the yield stress of the doubler plate is considerably smaller than that of the column web, it should be noted that the doubler plate can not provide the expected increase of the panel zone strength because the earlier yielding of the doubler plate causes the very little participation of the doubler plate in resisting panel zone shear.

To accurately predict local deformation demands and overall responses of structural systems under earthquake loadings, the analytical elements for the structural components should be able to accurately model the mechanical behavior of the structural components. Since the developed panel zone element has the capability to reasonably describe the mechanical behavior of the panel zone as shown in the above discussion, it can more accurately predict local deformation demands and overall responses than the bilinear panel zone element. The comparison of overall responses obtained

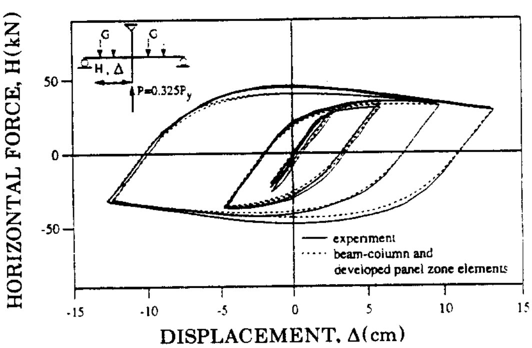


Fig. 14 Comparison of Test and the Analysis Using the Developed Panel Model for Overall Response for Krawinkler Specimen A1(Krawinkler 1971)

by the test and the analysis using the developed panel zone element for Krawinkler specimen A1 is shown in Fig. 14. The agreement between the experimental and analytical overall responses is much better as compared to the bilinear model predictions(Fig. 2).

4. Conclusions

The objective of the study in this paper was to develop a model to describe cyclic panel zone behavior of the bare steel beam-to-column joints. Hysteretic rules for cyclic loading were developed and the parameters needed for the developed hysteretic rules were determined through calibration with available experimental data. From the comparison of the analytical results with test data for the specimens with a doubler plate, it was found that doubler plates were only partially effective in resisting the panel zone shear. More tests are needed to further study the effectiveness of doubler plates according to the method used to connect them to the column. In spite of the simplicity of the model, reasonable agreement was established between model predictions and test results for panel zones. The developed panel zone element could produce better overall responses and local deformations than the bilinear panel zone element.

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