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Shape Optimization of Shear-type Hysteretic Steel Damper for Building Frames using FEM-Analysis and Heuristic Approach

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Abstract
An optimization approach is presented for improving energy dissipation capacity of a passive control device under cyclic deformation. A general purpose finite element software package is combined with a heuristic optimization algorithm. It is demonstrated in the numerical examples that the performance of a shear-type hysteretic steel damper can be successfully improved by optimizing the geometry of the device and the thicknesses of the stiffeners.
Keywords: *Shape Optimization, Tabu Search, Energy Dissipation Capacity, Shear-Type Steel Damper*

1. Introduction

Recently, shear-type hysteretic steel damper is extensively used for passive control of seismic responses of building frames. The damper is located between the upper and lower beams of a story, and consists of a low-yield-point steel panel that dissipates seismic energy under forced interstory. The panel is stiffened by several stiffeners to prevent local buckling that leads to premature fracture before a sufficient amount of energy is dissipated. However, in the existing shear-type hysteretic steel dampers, the locations and thicknesses of stiffeners are empirically or intuitively decided by the engineers, and the performance of the damper is confirmed by a physical test under static cyclic loading.

The first author demonstrated through a series of studies that the performances of structural parts including beams and braces can be successfully improved through heuristic optimization algorithms combined with high-precision finite element analysis [1,2]. In this study, we optimize the locations and thicknesses of the stiffeners as well as the aspect ratio of the shear-type steel damper. The elasto-plastic responses under static cyclic loading are evaluated using a general-purpose finite element analysis software package called ABAQUS [3]. The constitutive relation of the low-yield-point steel is defined using a nonlinear isotropic-kinematic hardening model. The parameters of the constitutive model are identified from the existing material test results under uniaxial cyclic loading. The panel, flanges, and stiffeners are discretized into shell elements.

Since the optimization problem is highly nonlinear, we discretize the variables into integer values and formulate the problem as a combinatorial optimization problem. A heuristic optimization algorithm called tabu search [4] (hereafter referred to as TS), which is based on a single-point local search, is used for obtaining approximate optimal solutions within a small number of function evaluations. For this purpose, a tool is developed using a script language called Python for automatically exchanging the data between the ABAQUS and the optimization program.

It is demonstrated in the numerical examples that the performance of a shear-type hysteretic steel damper can be successfully improved by optimizing the thicknesses and locations of the stiffeners, as well as the aspect ratio of panel. By utilizing this tool, the cost and the time period for development of passive control devices can be drastically reduced and the performances of the devices can be significantly improved.

2. Optimization algorithm

2.1 Outline of the TS

A heuristic optimization algorithm called TS, which is classified as a single-point local search [4,5], is used to obtain approximate optimal solutions within a small number of function evaluations. In contrast to a population-based approach such as genetic algorithm, TS has single solution at each step of local search. Therefore, TS is more suitable than a genetic algorithm for structural optimization problems that demand large computational cost for response evaluation. TS basically moves to the best neighborhood solution even if it does not improve the current solution. A tabu list is used to prevent an unfavorable phenomenon called cycling, in which several solutions are selected alternatively. Let $\mathbf{J} = (J_1,.., J_m)$ denote the vector of m design variables for a combinatorial optimization problem to maximize the objective function $F(\mathbf{J})$. The basic algorithm of TS is summarized as follows:

Step 1 Randomly generate a seed solution $\mathbf{J} = (J_1,.., J_m)$ and initialize the tabu list T as $T = \{\mathbf{J}\}$. Evaluate the objective function and initialize the incumbent optimal objective value as $F_{\mathrm{opt}} = F(\mathbf{J})$.

Step 2 Generate a set of q neighborhood solutions $\mathbf{J}^{\mathrm{N}j} = (J^{\mathrm{N}j}{}_1,.., J^{\mathrm{N}j}{}_m)$, ($j$=1, …, q) from $\mathbf{J}$, and evaluate the objective function of each solution.

Step 3 Among the solutions in the set $\{\mathbf{J}^{\mathrm{N}1}, \dots, \mathbf{J}^{\mathrm{N}q}\}$, select the best one that has the maximum value of objective function, and is not included in the list T. Assign the best solution as the new seed solution $\mathbf{J}$.

Step 4 Update the incumbent optimal objective function as $F_{\mathrm{opt}} = F(\mathbf{J})$ when the value is improved.

Step 5 Add the seed solution $\mathbf{J}$ to the list T if the size of tabu list is less than the prescribed limit.

Step 6 Output F_{opt} and the corresponding optimal solution, if the number of iterations reaches the specified value; otherwise, go to Step 2.

In Step 2, the neighborhood solution $\mathbf{J}^{\mathrm{N}j} = (J_1^{\mathrm{N}j}, \dots, J_m^{\mathrm{N}j})$ is as defined follows using uniform random numbers r:

$$r < 0.3333: \quad J_i^{\mathrm{N}j} = J_i - 1 \tag{1a}$$

$$0.3333 \le r < 0.6667: \quad J_i^{\mathrm{N}j} = J_i \tag{1b}$$

$$r \ge 0.6667: \quad J_i^{\mathrm{N}j} = J_i + 1 \tag{1c}$$

2.2 Formulation of optimization algorithm

The TS has been developed for optimization problems with integer variables. Therefore, the design variables are discretized into integer values. Real variables $X_1, \dots, X_m$ are defined by integer variables $J_1, \dots, J_m$ with the specified standard value X_{i0} and increment ΔX_i as

$$X_i = X_{i0} + J_i \Delta X_i \quad (i = 1, \dots, m) \tag{2}$$

Therefore, all responses of analysis are functions of $\mathbf{J}$.

The objective function is the total dissipated energy E_{p}. We maximize E_{p} under a constraint $g(\mathbf{J}) \le g_0$, which is defined for each optimization problem. Let s_i denote the number of sampling values that J_i can take. The optimization problem is formulated as follows:

$$\text{Maximize} \quad \mathrm{F}(\mathbf{J}) = \mathrm{E_p}(\mathbf{J}) \tag{3a}$$

$$\text{subject to} \quad g(J) \le g_0 \tag{3b}$$

$$J_i \in \{1, 2, \cdots, s_i\}, \quad (i = 1, \dots, m) \tag{3c}$$

2.3 Optimization Process

Fig. 1 shows the data flow between TS and FE-analysis using ABAQUS Ver.6.10.3 [3]. The pre-process and post-process are carried out using the Python script. The computations of functions and the process of TS are coded using Fortran.

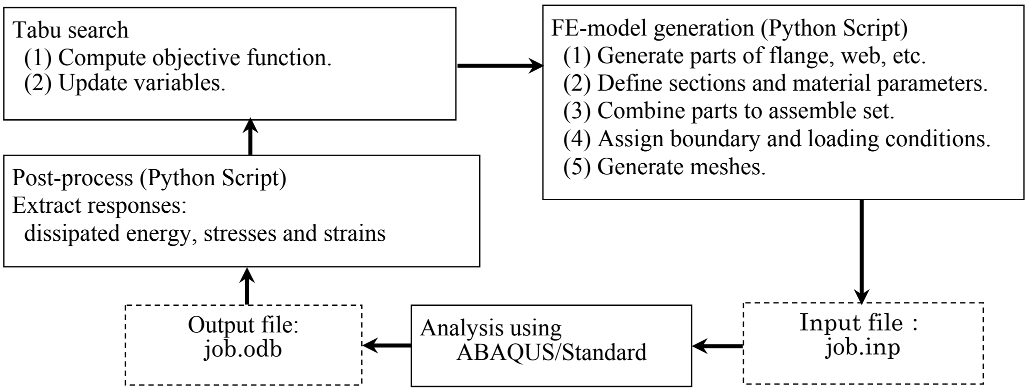

Figure 1. Optimization algorithm using TS and ABAQUS.

3. Shear-type hysteretic steel damper

3.1 Standard Model

The experimental specimen of the shear-type hysteretic steel damper is shown in Fig. 2. The size of the specimen is 2/3 of the real size. The specimen is a stud-type viscoelastic damper, which is extensively used as passive control device of seismic responses of building frames. The material of center panel of the device, as shown in hatched area in Fig. 2, is a low-yield-point steel. When the device is attached between the beams, the panel yields due to the interstory shear force prior to the bracket of the device and other members of a frame. This way, the panel zone can absorb the earthquake energy efficiently without damaging other parts. The buckling restraining stiffeners are assigned to prevent premature out-of-plane buckling of the panel. The stiffeners are located longitudinally in the front side, and laterally in the rear side of the panel.

The material of the panel, flanges, and buckling restraining stiffeners are LY100 (low-yield-point steel), SM490A, and SS400, respectively. The values of Young's modulus E, Poisson's ratio v, yield stress σ_y, and tensile strength σ_u obtained by uniaxial tests are listed in Table1.

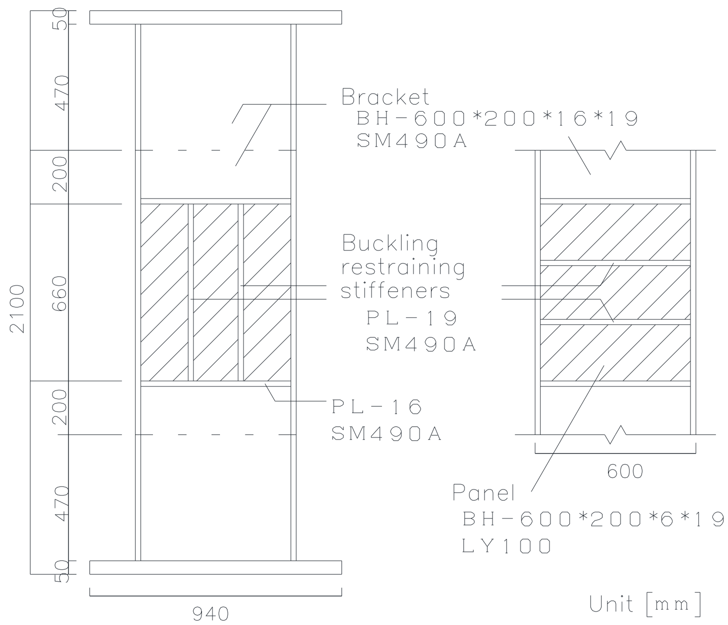

Figure 2. An experimental specimen; left: front side, right: rear side)

A finite element model called the standard model is generated from the experimental specimen in Fig.2. The finite-element mesh is generated using python script. A quadrilateral thick shell element called S4R is used, and the nominal size of mesh is 40 mm for automatic mesh generation.

A constant distributed load that is equivalent to a compressive axial force of 710 kN is first applied at the top plate prior to the forced horizontal cyclic deformation. The loading program of the static shear force of five cycles is controlled by the peak drift angle of 1/60 rad. There have been many criteria for ductile fracture of steel materials. However, we use the equivalent plastic strain as a measure of damage of the material, because most of the criteria are based on the equivalent plastic strain.

The results of standard model are shown in Table 2, where E_p, ε_{max}, R_{max}, and M_{max} denote the total dissipated energy, the maximum equivalent plastic strain among all elements, the maximum horizontal reaction force, and the maximum reaction moment, respectively.

Table 1. Material properties

	E (kN/mm^2)	ν	σ_y (N/mm^2)	σ_u (N/mm^2)
LY100	200	0.3	98	254
SM490A (PL-19)	200	0.3	345	537
SM490A (PL-16)			367	545
SS400	200	0.3	368	442

Table 2. Analysis Results

	E_p(kN·m)	ε_{max}	R_{max}(kN)	M_{max}(kN·m)
Standard Model	201.2	0.867	481.5	956.5

Fig. 3 shows distribution of equivalent plastic strain of the standard model at final step. It can be observed from this figure that the equivalent plastic strain has larger values mainly in the red region around the center of the shear panel.

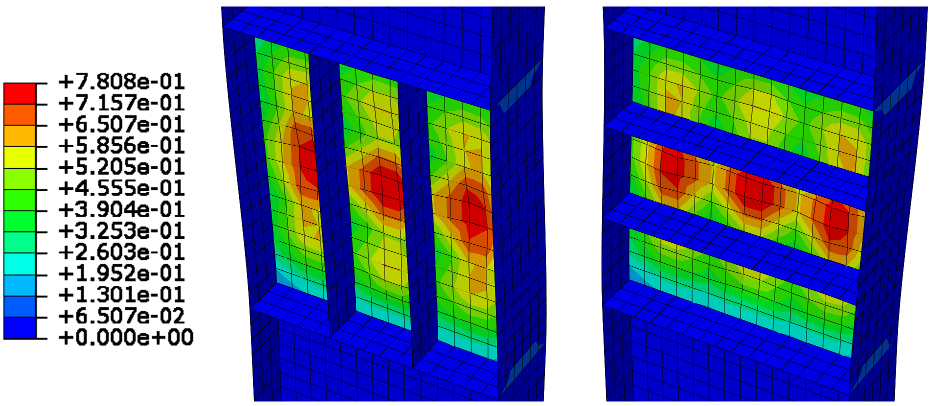

Figure 3. Distribution of equivalent plastic strain of the standard model at final step; left: front side, right: rear side.

4. Optimization of the shear-type hysteretic steel damper

In this section, we demonstrate in the numerical examples that the performance of a shear-type hysteretic steel damper can be successfully improved by optimization. The locations and thicknesses of the buckling restraining stiffeners are optimized. The aspect ratio of the panel is next optimized. Finally, all variables in the first and second problems are optimized. The objective function to be maximized is the total dissipated energy E_p when the maximum value of equivalent plastic strain among all elements reaches ε_{max} of the standard model shown in Table 2.

4.1 Optimization of locations and thicknesses of buckling restraining stiffeners

In this optimization problem, the vector of design variables consists of the locations of the buckling restraining stiffeners (J_1, J_2) and the thicknesses of the stiffeners (J_3, J_4). In order to preserve the symmetry, the numbers of independent variables for location and thickness are one, respectively, for the stiffeners in front and rear. The location X_i

of the stiffeners at each side is defined by J_1 and J_2 as

$$X_i = J_i \Delta X_i \qquad J_i \in \{1, 2, \cdots, 7\}, (i = 1, 2) \tag{4}$$

where ΔX_1 and ΔX_2 are 1/18 of the width and height of the panel, respectively.

The independent variables for thicknesses T_1 and T_2 of the stiffeners in two sided are defined by S_1 and S_2 as

$$T_i = 0.002 + S_i \Delta T_i, \quad S_i \in \{1, .., 8\}, (i = 1, 2) \tag{5}$$

where ΔT_1 and ΔT_2 are 0.001 m.

For the TS, the number of neighborhood solutions is q = 4, and the number of steps n = 15. Optimization is carried out from three different random initial solutions to investigate dependence of the optimal solution on the initial solution. The maximum value 239.7 was obtained for E_p in two trials; therefore, this solution is regarded as the optimal solution. The optimal values of integer variables are (J_1, J_2, S_1, S_2) = (3, 1, 7, 6). The solution is hereafter called the optimal solution S. As the result of optimization the total dissipated energy E_p was improved by 19.1 %from the standard model. The distribution of equivalent plastic strain of the optimal solution S at final step is shown in Fig. 4.

In this optimal solution, the lateral buckling restraining stiffeners in the rear side are shifted to the center and the thicknesses of stiffeners in both sides are increased from the standard model. It is seen from Figs. 3 and 4 that the equivalent plastic strain has large value in wider region as a result of optimization so that the large deformation around the center of the standard model is restrained by moving the lateral stiffeners in the rear side to the center. This way, the energy dissipation property can be improved through this optimization.

In this model, the effect of optimization is summarized as follows:

1. More energy can be dissipated to increase the area of large plastic deformation.
2. The maximum equivalent plastic strain can be reduced by increasing the stiffnesses of the stiffeners; hence, the number of cycles before reaching the specified bound of maximum strain can be increases.

Note that a too much increase of the stiffness in the panel leads to a large deformation of brackets, and accordingly, small deformation of the panel. Therefore, the most appropriate thicknesses of the buckling restraining stiffeners have been selected by optimization.

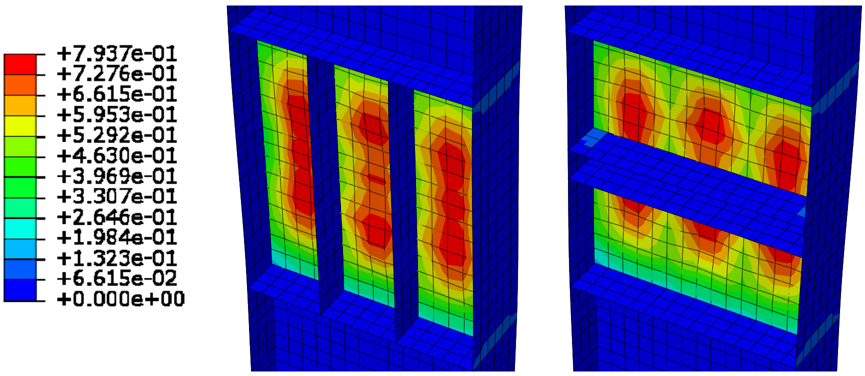

Figure 4. Distribution of equivalent plastic strain of Model S at final step; left: front side, right: rear side.

4.2 Optimization of aspect ratio of the panel

We next optimize the aspect ratio of the panel. In order to preserve symmetry property, the independent variables are the panel width H_1 and the panel height H_2, which are defined by two integer variables K_1 and K_2 as

$$H_1 = (K_1 + 7)\Delta H_1 \qquad K_1 \in \{1, 2, .., 5\} \tag{6a}$$

$$H_2 = (K_2 + 7)\Delta H_2 \qquad K_2 \in \{1, 2, .., 8\} \tag{6b}$$

where ΔH_1 and ΔH_2 are 1/10 of the width and height, respectively, of the panel of the standard model.

The enumeration method is used here, because the number of variables is 2, and the small numbers 5 and 8 are assigned for sampling values of the variables. The constraints are added to consider the influence of the design modification of the panel on the responses of building frames; i.e., the maximum horizontal reaction force R_{max} and the maximum reaction moment M_{max} should be less than the values of the standard model as shown in Table 2. As the result of enumeration, the maximum value of E_p is 263.8 corresponding to the optimal solution (K_1, K_2) = (4, 7). This solution is hereafter called the optimal solution W, the solution achieved 31.1% increase of the total dissipated energy E_p from the standard model. The distribution of equivalent plastic strain of the optimal solution W at final step is shown in Fig. 5.

The optimal solution W has larger panel width and panel height than those of the standard model. Hence, the increase of the panel volume as a result of optimization leads to the improvement of energy dissipation property. However, if the height becomes too large, then the average shear angle is reduced, and we cannot have enough plastic deformation in the panel. Therefore, the height did not reach its upper bound through optimization.

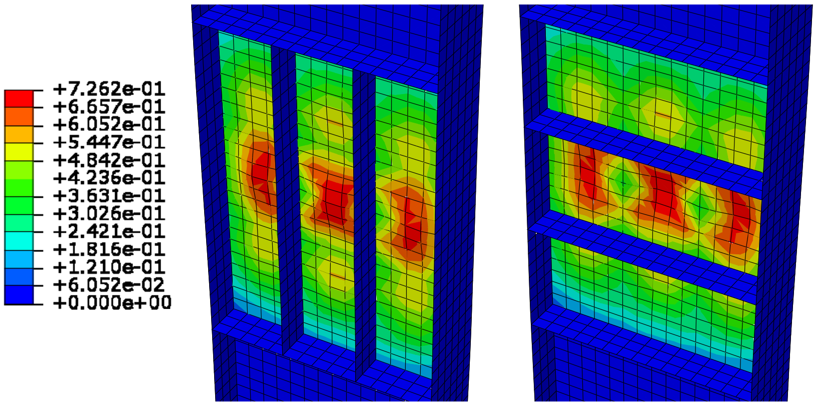

Figure 5. Distribution of equivalent plastic strain of Model W at final step;
left: front side, right: rear side.

4.3 Simultaneous optimization of stiffeners and aspect ratio

In this section, we optimize the thicknesses and locations of the buckling restraining stiffeners, as well as the aspect ratio of the panel, simultaneously. Hence, the vectors of design variables are J, S and K defined in Secs. 4.2 and 4.2. TS is used for optimization with the number of neighborhood solutions q = 6 and the number of steps n = 15.

Optimization was first carried out from a randomly generated initial solution under constraints on reaction force and moment defined in Sec. 4.3 to obtain the maximum value 314.5 for E_p by the solution $(J_1, J_2, S_1, S_2, K_1, K_2)$ = (3, 1, 7, 3, 4, 8). This solution was found at the 13th step, which is nearly the end of the total 15 steps. Therefore, optimization of 15 steps was carried out again from this solution to obtain the maximum value 322.9 of the E_p by the optimal solution $(J_1, J_2, S_1, S_2, K_1, K_2)$ = (3, 1, 8, 5, 4, 8).

The solution is hereafter called the optimal solution SW, which achieves 60.5% increase of the total dissipated energy E_p from the standard model. The distribution of equivalent plastic strain of the optimal solution SW at final step is shown in Fig. 6. Since S_1 and K_2 of the optimal solution SW have their upper-bound values, it is possible to optimize these variables with larger upper bounds.

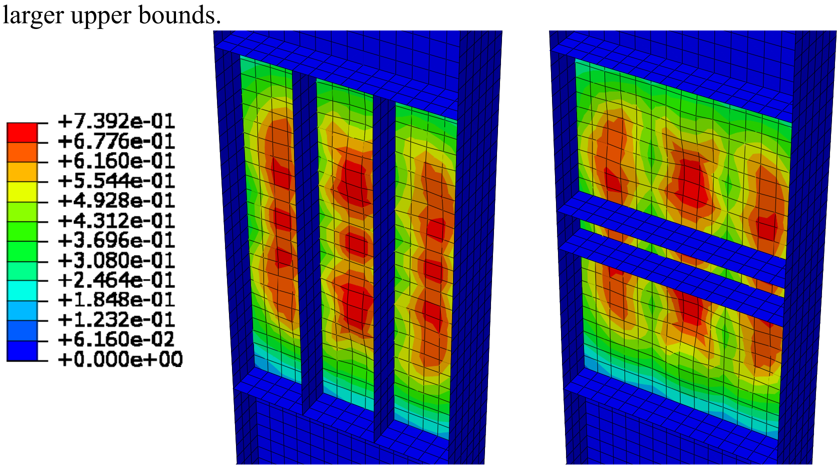

Figure 5. Distribution of equivalent plastic strain of Model SW at final step;
left: front side, right: rear side.

5. Discussions on performance of optimization

Optimization results are summarized in Table 3. In the optimal solution S, the maximum performance is achieved through optimization of stiffeners using the panel of the standard model. On the other hand, in the optimal solution W, the geometry of panel is also improved. The performance of device is further improved by the optimal solution SW through simultaneous optimization of the stiffeners and the panel.

Table 3. Optimization Results

	E_p(kN・m)	ε_{max}	R_{max}(kN)	M_{max}(kN・m)
Standard Model	201.2	0.867	481.5	956.5
Optimal Solution S	239.7	0.865	492.1	977.9
Optimal Solution W	263.8	0.866	474.1	947.1
Optimal Solution SW	322.9	0.863	470.1	942.9

The important point for structural optimization problems is to reduce the number of analyses to obtain an approximate optimal solution, because structural analysis problems are computationally expensive.
The number of analyses N_{opt} is defined for TS as

$$N_{opt} = qn - N_{tabu} \tag{7}$$

where N_{tabu} is the number of solutions rejected by the tabu list. In the optimal solution S, the total number of N_{opt} for three trials is 173 (the total number of possible combinations is 3136). In the optimal solution SW, the total number of N_{opt} for two consecutive optimization processes is 178 (the total number of possible combinations is 125440). Therefore, it may be concluded from these results that approximate optimal solutions can be successfully found with small number of analyses using TS algorithm. A PC with Intel Xeon W3680 (3.33 GHz) and 12 GB memory is used for the computations. Although the PC has six cores, only single core is available for computation using ABAQUS, and the CPU time is 439 seconds in the case of standard model.

6. Conclusions

Optimization has been carried out for a shear-type hysteretic steel damper subjected to static cyclic deformation. The objective function is the total dissipated before the maximum equivalent stress reaches the specified value. The conclusions drawn from this study are summarized as follows:

1. Energy dissipation property successfully improved by optimizing the shape of the panel, as well as the locations and the thicknesses of the stiffeners. About 60% of the total dissipated energy has been increased as a result of optimization from the standard model.
2. A heuristic approach called TS can be effectively used to obtain an approximate of a computationally expensive structural optimization problem with practically acceptable small number of function evaluations.
3. A FE-analysis software package ABAQUS can be combined with an optimization algorithm using the Python script.

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