# SUB-STRUCTURE ONLINE TEST ON VIBRATION CONTROL OF STRUCTURES COUPLED WITH FRICTION DAMPER

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## ABSTRACT :

Sub-structure online seismic tests were conducted to investigate effects of the friction damper on seismic behavior of a composite structure consisting of an old concrete structure and a new steel frame. The concrete building represented an existing structure that doesn’t satisfies the seismic requirements in the current design code, while the steel building was coupled with the concrete building by friction damper aimed to upgrade the seismic capacity of the concrete building.

The online test results have indicated that the cyclical behavior of the friction damper made of steel plate and aluminum plate could be accurately simulated with the so-called perfect elastic-plastic model without degradation in stiffness. It has also been verified that the seismic performance of the composite structures could be accurately predicted if one use the perfect elastic-plastic model to simulate the behavior of the connecting friction damper.

In addition, the tests have shown that the use of friction damper to connect an existing unfit concrete building and a new steel building could effectively reduce their displacement response and acceleration response simultaneously. The mitigation degree due to the friction damper on the seismic response of the composite structures depends upon the relative stiffness of the two buildings, the natural periods, and the mass ratio of the two buildings.

**KEYWORDS:** Sub-structure online test, existing unfit concrete building, friction damper, relative stiffness, mass ratio, displacement response

## 1. INTRODUCTION

In recent years, enhancement in seismic capacity of existing reinforced concrete (RC) buildings has become an urgent problem as pointed out by [JSSC, 2002] and [JMES, 2005]. Particularly for the existing RC school building, seismic retrofitting is sometimes required not only for upgrading the seismic capacity, but meanwhile for adding new architectural functions as well. This requirement apparently presents a new challenge to engineers.

To meet this challenge, an alternative seismic retrofitting method has been proposed as reviewed in reference 3 through reference 6. In this method, a new steel building that meets the architectural requirement will be connected to the existing RC building via energy dissipaters such as dampers. Some researches on the connected structures have been conducted in Japan recently by [Zhang et al, 2006], [Fujitani et al., 2006], [Iwanami et al., 2006], and [Kageyama et al., 2000]. In these previous studies the optimum vibration control principal solutions as well as the optimum design of various dampers have already been tested. However, the friction damper has not yet been attempted in the connected structure system though it has the advantage that the mechanism can be simply adjusted and the damping force can be controlled simply by the number of bolts and upon tightening force introduced in the bolts [Gregorian et al, 1993] and [Tomokazu et al., 2003].

In this research, the effect of the friction damper as an energy dissipation device connecting the new steel structure with the existing RC structure is examined thorough pseudo-dynamic on-line test on substructure. The substructure online earthquake response experiment [Takahashi et al., 1980] has been done to verify the application possibility of the connected structures with the friction damper and to obtain fundamental information on the mitigation effect of the connecting friction damper on the seismic response of the composite structures.

## 2. OUTLINES OF THE EXPERIMENT

### *2.1. Details of the Connecting Damper*

The friction damper studied in this paper is shown Figure 1. As obvious in Figure 1, the damper consists of two T-shapes steel plates. The upper part and the lower part of the damper were connected through M20 high-tensile strength bolts, whose horizontal center line is parallel to the lateral loading line. Upon tightening of

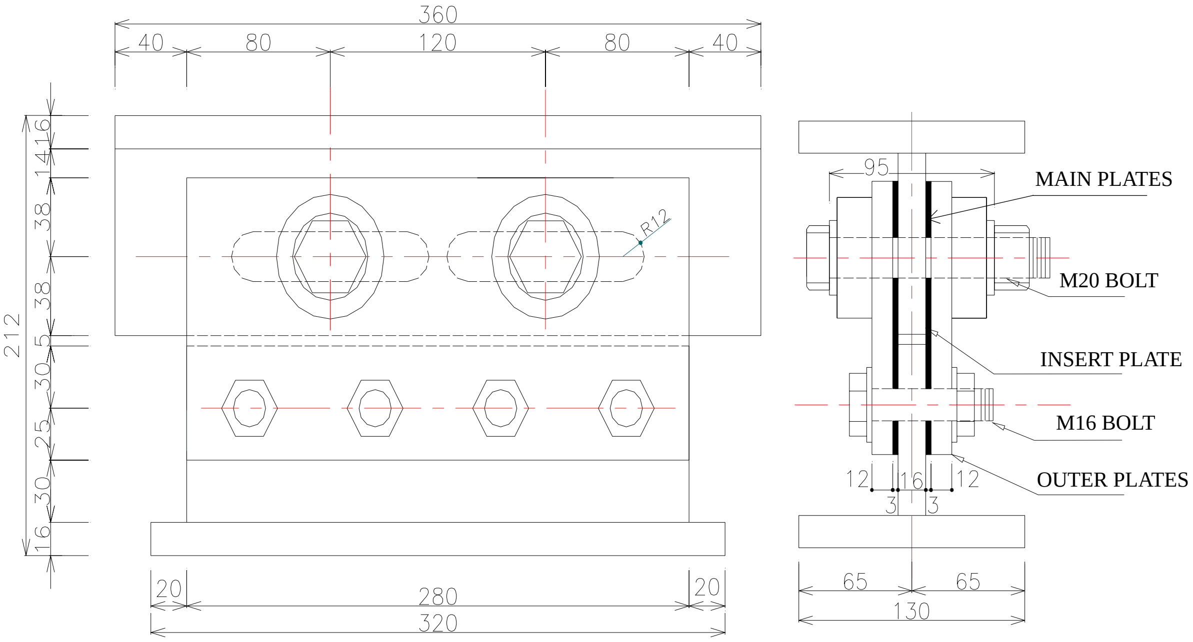


Figure 1 Details of the friction damper

Table 2.1 Data for beams under dynamic loading

| Material | Plates thickness (mm) | Yield strength ($N/mm^2$) | Ultimate strength ($N/mm^2$) | Elongation (%) | Shearing Yield strength ($N/mm^2$) |
|---|---|---|---|---|---|
| Aluminum (A2017P-T3) | 3.05 | 357.0 | 435.0 | 15.0% | 206.1 |
| SN490 steel | 15.77 | 423.8 | 589.0 | 45.6% | 244.2 |

the bolts, the main plates are “sandwiched” between the aluminum insert plates. The holes in the aluminum insert plates and in the steel outer plates are of standard size. When the lateral loading applied to the connection and exceeds the frictional forces developed between the frictional surfaces, the main plate begins to slip relative to the aluminum insert plates. This process repeats with slip in the opposite direction until reversal of the lateral force applied. Then energy is dissipated by means of friction between the slip surfaces. On the other hand, the lower part of the damper’s T-shape steel plate is fixed by four M16 bolts. The rectangular hole of 24mm in width and 110mm in length was installed in the main plate. For getting higher friction force, the shot blast processing is given to the outer steel plate (SS400, yield strength 288 $N/mm^2$, Ultimate strength 400 $N/mm^2$) and roughing the surface (maximum height R may become 50μm or more) so that sliding surfaces is limited between the main plate and the aluminum plate.

The experimental variables are the amplitude of tensile force introduced to the bolts and the displacement

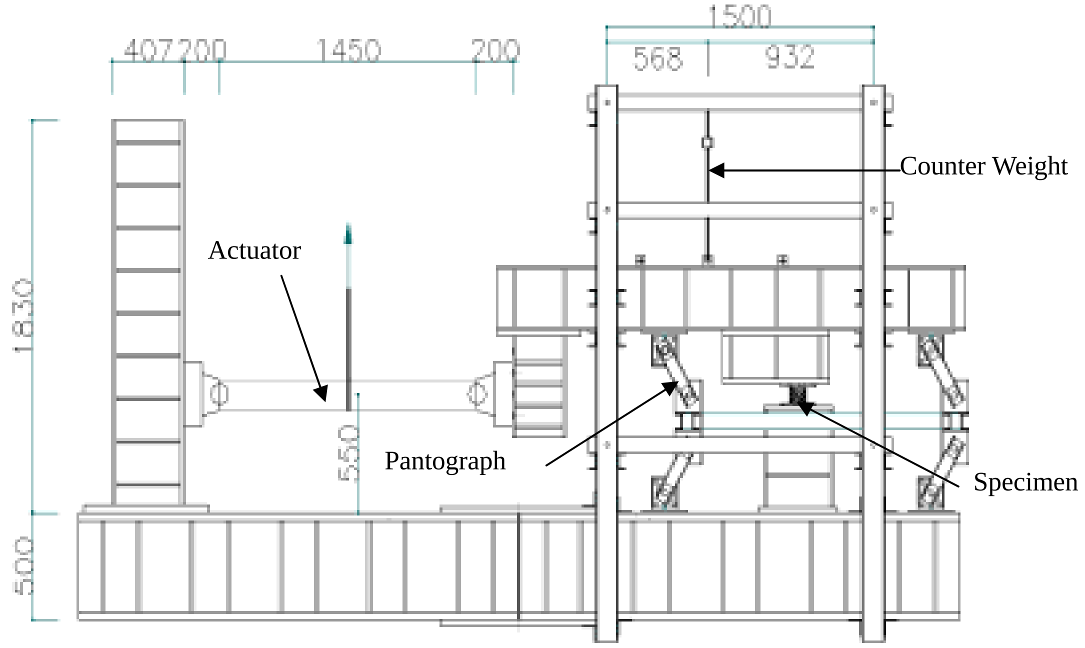


Figure 2 Loading Equipments

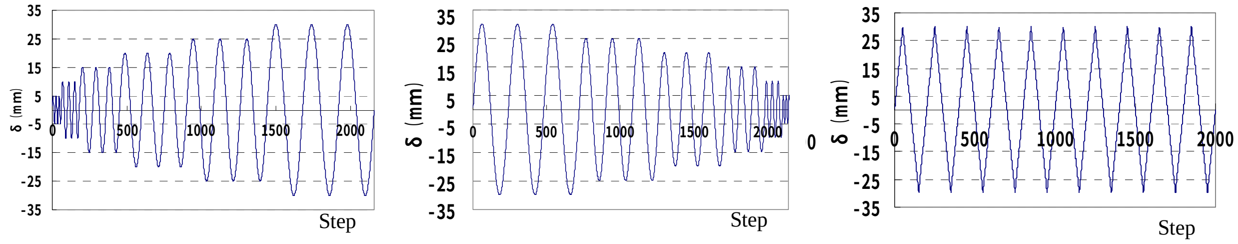


Figure 3 Typical Loading Program

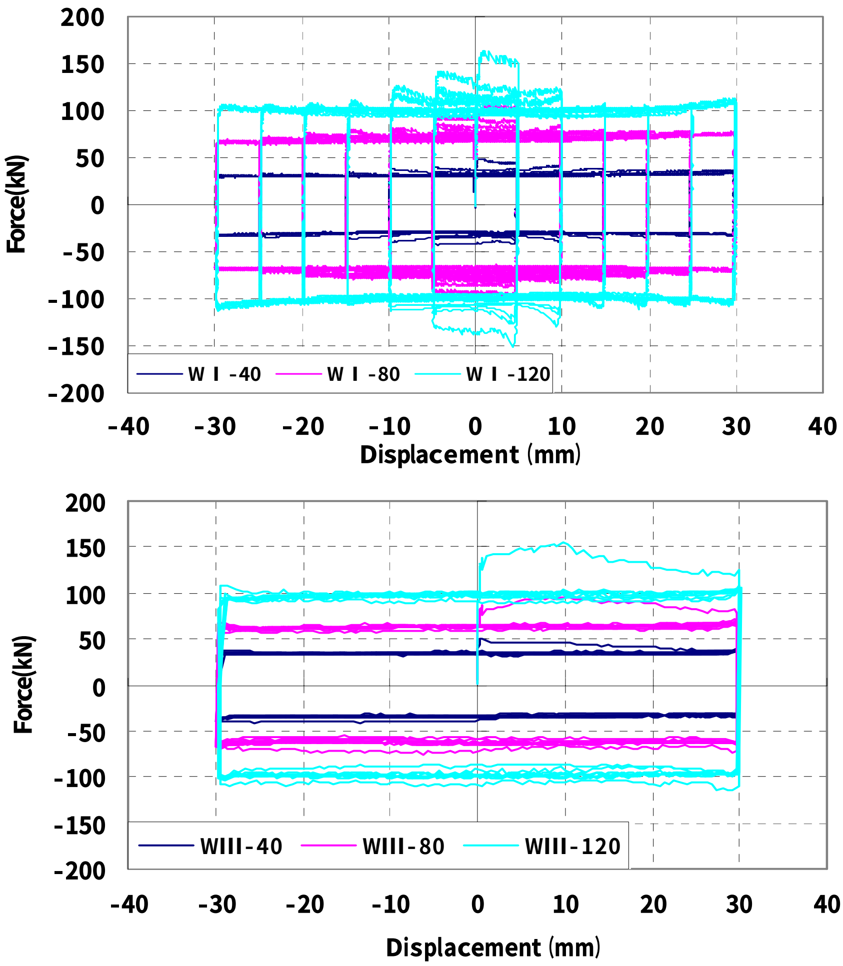


Figure 4 Examples of the measured cyclical lateral force versus slip relationship

history. The tensions had amplitudes of 40kN, 80kN, and 120kN. And the mechanical properties of the materials used in the friction damper have been summarized in Table 2.1.

### *2.2.Loading Set-up and Measurements*

The test specimens were placed within the experimental loading frame as shown in Figure 2. The actuator can apply cyclically reversed lateral forces up to 200kN with a maximum displacement stroke of 35mm. A pantograph was used to make the reversal of the lateral keep in horizontal direction. All tests were done under displacement control. A total of five loading programs were planned, and Figure 3 shows examples of the planned loading program.

Horizontal load applied to the specimen was measured through a load cell built into the actuator. Moreover, the speed of load is about 1mm/sec in all loading cycles. And displacement was measured by displacement sensors built into the side of specimen. Horizontal load and displacement were monitored and recorded using a Data Acquisition System in conjunction with a computer.

## 3. EXPERIMENTAL RESULTS AND DISCUSSIONS

Figure 4 shows typical examples of the test results for the dampers in terms of the relationship between the lateral force and the lateral slip (displacement). In each figure, three hysteresis loops are plotted to express dampers under three different tightening tensions introduced to the bolts, respectively.

From Figure 4, one can draw several observations on the cyclical properties of the friction dampers as listed below:

1) The friction damper can dissipate energy stably up to large deformation, and its hysteresis loop curve can be approximated accurately with the famous elastic-perfectly-plastic model.
2) The lateral force resistance of the friction damper increases almost proportionally with the tensile force introduced to the bolts. The displacement history doesn't influence the lateral force resistance significantly.
3) At the stage of small slip, the friction damper exhibits a much higher lateral force resistance than the stable lateral force observed in large deformation. This can be mainly attributed to that the static friction coefficient of the aluminum plates used is larger than the dynamic friction coefficient.
4) When modeling the energy-absorption hysteresis loop of the friction damper, for simplicity and design efficiency, the stable lateral force capacity should be used to express the yield force rather than the maximum force observed in the initial loading stage, since the initial higher lateral force is unstable.

Figure 5, shows experimental results of the maximum lateral force Qmax and the stable friction force Qsta. From the test results shown in Figure 5, the stable friction force can be simply evaluated in form of

$$Q_{sta} = 0.92T_0 - 2.40 \quad (in\ kN) \tag{3-1}$$

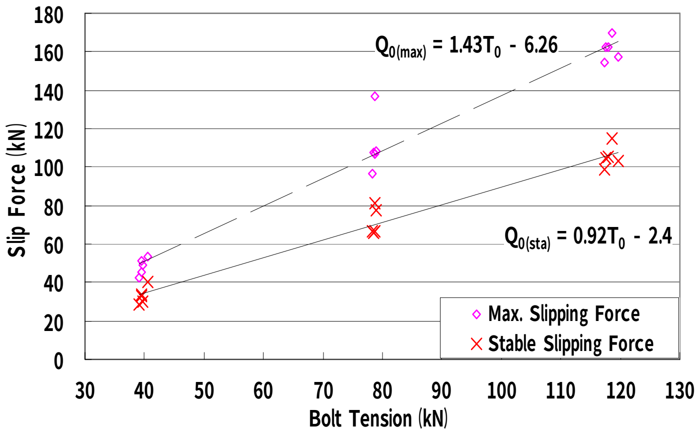


Figure 5 Observed Stable Friction Force

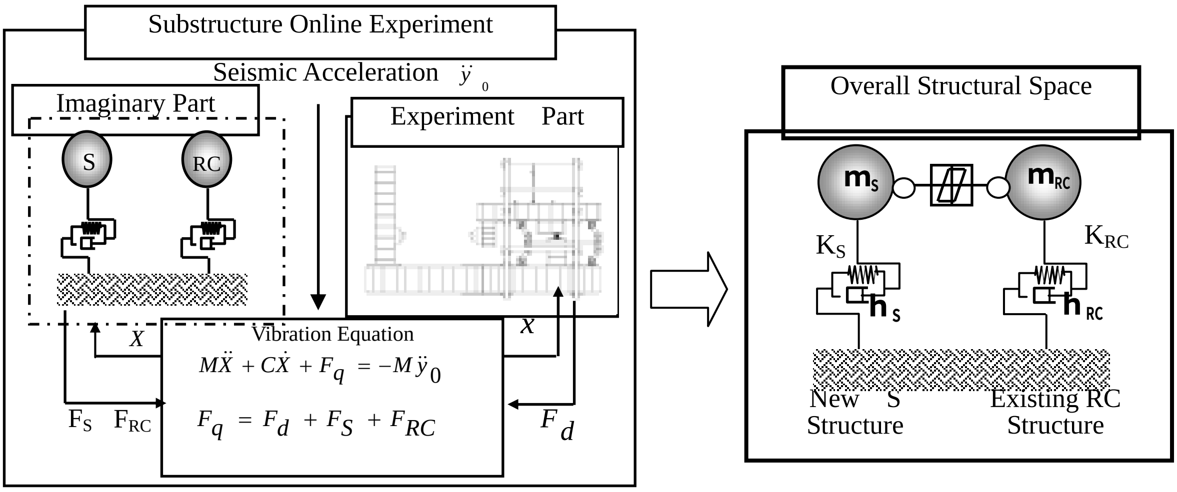
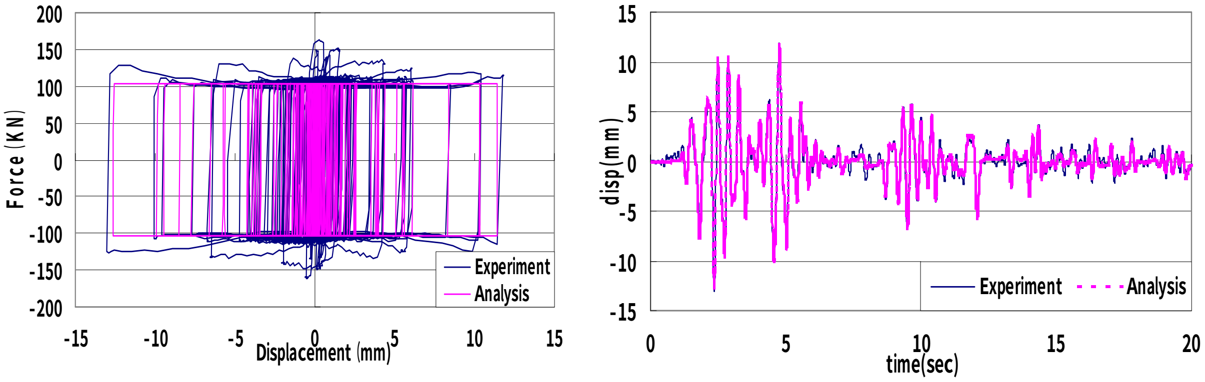


Figure 6 Outline of the Pseudo-Dynamic Online Test

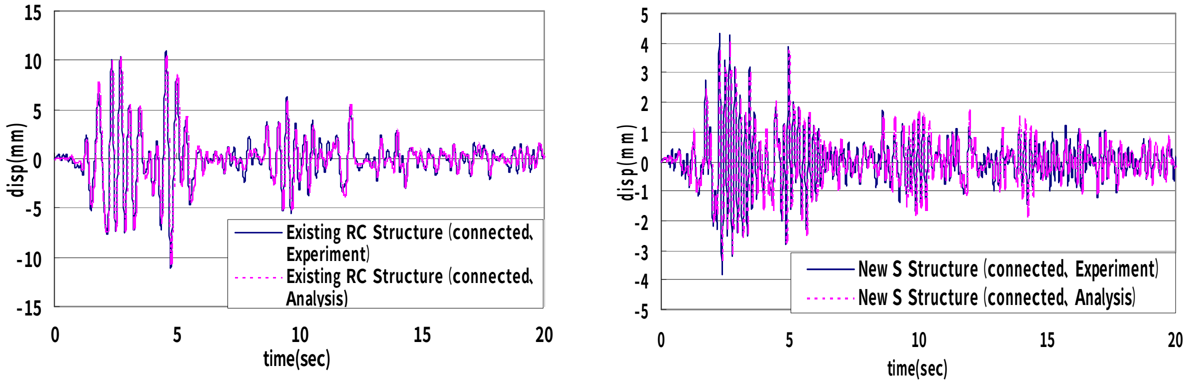
Table 4.1 Details of the Simulation Model

| Test Code | $T_s/T_{RC}$ | $T_{RC}$ (sec) | $T_s$ (sec) | $W_{RC}$(KN) | $W_S$(KN) | Shearing force (kN) | Input Earthquake acceleration | |
|---|---|---|---|---|---|---|---|---|
| | $M_S/M_{RC}$ | | | $K_{RC}$(kN/cm) | $K_S$(kN/cm) | | Maximum scale acceleration | Input time |
| 1 | 0.5 | 0.19 | 0.38 | 490 | 735 | 103 | El Centro1940(NS) | |
| | 1.5 | | | 136.6 | 819.3 | | 200gal. | 20sec |



(a) Hysteresis loop (b) Displacement response

Figure 7 Comparison of the Measured and Theoretical Seismic Response of the Damper



(a) RC structure (b) Steel structure

Figure 8 Displacement Response of the RC Structure and the Steel Structure

where $T_o$ is the tension in the bolts. Eqn. 3-1 will be used to evaluate the yield friction force as modeling the hysteresis loop of the friction damper by the famous elastic-perfectly-plastic model.

## 4. SUBSTRUCTURE ONLINE TESTS

Figure 6 shows outline of the so-called sub-structure online test of the connected structures by the friction damper as energy-dissipater. A friction damper with a stable friction force of 103kN connects a new steel structure with an existing RC structure. Seismic response of the connected structures was analyzed by using a substructure online test program. In the dynamic analysis, central difference step-by-step integration method was used. The structures were assumed to behave as a shear structure, and the friction damper as an elastic-perfectly-plastic connection. The steel structure and the existing RC structure's viscous damping were assumed to be 2% and 3%, respectively. Furthermore, it was also assumed that the two structures both remain elastic in the whole acceleration histories for simplicity. Table 4.1 lists main parameters in the two online tests conducted. El Centro NS 1940 acceleration record was used with the maximum acceleration scaled to 0.2m/s$^2$ and inputted for 20 seconds. The time interval was 0.005s.

As listed in Table 4.1, the online test was conducted to a connected structures system, where the mass of the new steel structure is half of the existing RC structure, while its natural period is twice of the RC structure. The yield friction force of the connecting friction damper was assumed to be 103 kN.

Figure 7 show the hysteresis diagram and slip displacement response of the friction damper. It can be seen from Figure 7 that the target yield friction force of 103 kN has been attained during the seismic analysis.

Figure 8 shows displacement responses of the existing RC building and the new steel structure obtained through the online test. The maximum displacement response of the RC structure was 17.8mm and the steel structure was 4.3mm when the two structures were not connected. On the other hand, as connected with the friction damper, the maximum displacement response of the RC structure and the steel structure were reduced to 11.1mm and 4.5mm,respectively. This fact implies that the friction damper can act effectively as an energy dissipater in the coupled structure system.

## 5. CONCLUSIONS

The shearing-type friction damper is capable of dissipating significant quantities of energy, which can be evaluated using the famous elastic-perfectly-plastic model. The maximum lateral force in the friction dampers depends on many factors such as the initial roughness of the aluminum plates, which results in higher static friction coefficient. When modeling the friction damper, the stable yield friction force is recommended (see Eqn.3-1) rather than the unstable maximum friction force.

The online test results indicate that the friction damper, when used to connect the two buildings, can reduce the displacement response of the existing reinforced concrete building significantly, which implies that the friction damper is suitable for the couple seismic retrofitting recently proposed.

In the online tests described in this paper, for simplicity, two building structures has been assumed to remain elastic during analysis. Effect of the friction damper on reduction of displacement of the structures that behave inelastic need to be further studied.

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