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Friction Damper in Steel Coupling Beams for Enhanced Seismic Resilience of High-rise Buildings

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Summary

A friction damper is proposed and tested for the use in steel coupling beams in high-rise buildings. Multiple brake pad-to-steel interfaces are jacketed by disc springs and high-strength bolts to yield stable frictional resistance. Damage is only likely to take place on the brake pad-to-steel friction interface. One can easily disassemble the damper and remove the brake pads by loosening the bolts, either for damage inspection or for replacement when necessary. Cyclic loading tests on steel coupling beams with the proposed friction damper were conducted to show the reliable frictional behavior of the chosen material. The inherent high initial stiffness of the friction interface and the well-defined frictional force without much over-strength make it possible to mimic the stiffness and yield strength of conventional RC or steel coupling beam counterparts, but with superior energy dissipating capacity and less variability of the strength demand for adjacent elements and joints.

Keywords: friction damper; steel coupling beam; friction coefficient; brake pad.

1. Introduction

Dual systems incorporating coupled shear walls/cores and perimeter frames have inherently multiple levels of seismic protection. In such systems, coupling beams that constitute the first defense level may deform significantly and thus concentrate most of the damage of the entire system during earthquakes [1]. From the seismic damage control's point of view, coupling beams emerges as favorable locations for supplemental damping devices (Figure 1a). A wide spectrum of dampers have been proposed for coupling beams, most of which are shear-type steel ones (e.g., [2][3][4]), while viscoelastic and shape memory alloy ones are also under consideration (e.g.,[5]). Chung et al. (2009) proposed to use friction dampers in the mid-span of coupling beams to control the seismic response of high-rise reinforced concrete buildings. Numerical analysis was conducted to demonstrate the efficiency of friction dampers in such uses [6].

In addition to the stable capacity of dissipating energy, friction dampers are also advantageous over many other categories of dampers for its large stroke, high initial stiffness and clearly defined maximum force that makes it easier to determine the strength demands for the connecting components. Besides, most friction dampers are easy to disassemble, making it possible to replace the friction pad to restore the full function of the damper when necessary. As a key issue in the development of friction dampers, various types of material have been tried out for the frictional interface. As compared to other candidates such brass (e.g.,[7][8]), bronze alloy (e.g., [9][10]) and aluminium alloy (e.g.,[11][12]), specially-designed brake pad has been accepted as a high performance frictional material in friction dampers (e.g., [13][14]).

In the present study, a friction damper is proposed for the use in steel coupling beam (Figure 1b). Multiple brake pad-to-steel interfaces are jacketed by disc springs and fastened by high-strength bolts to provide stable frictional behavior. Damage is only likely to take place on the brake pad-to-steel friction interface. One can easily disassemble the damper and remove the brake pads by loosening the bolts, either for damage inspection or for replacement when necessary (Figure 1c).

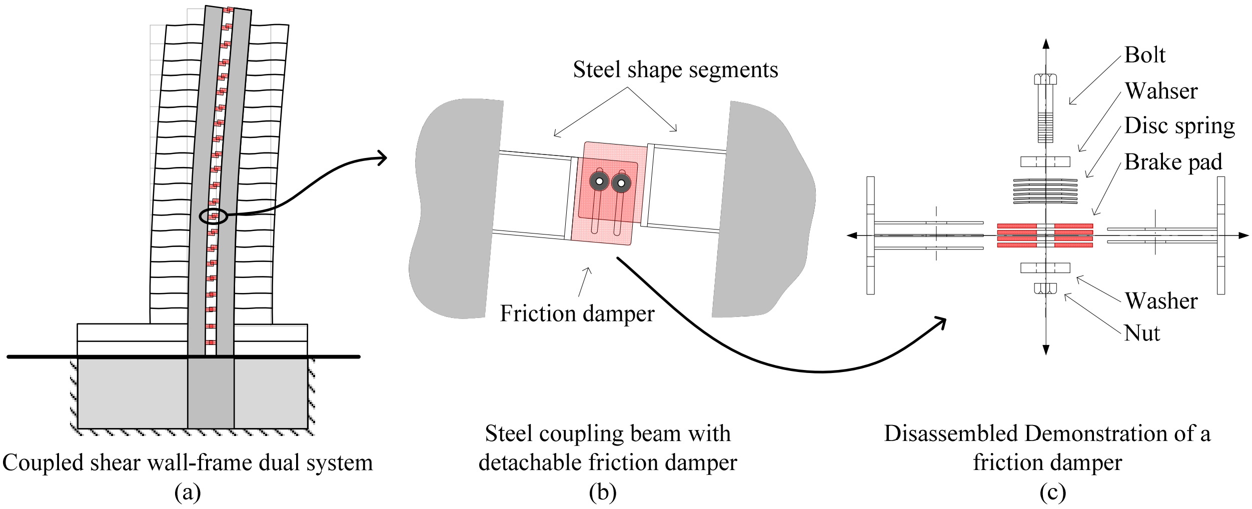

Fig. 1: Proposed friction damper and its use in steel coupling beams in high-rise building.

2. Prototype coupling beam

Cyclic loading test of a steel coupling beam equipped with the proposed friction damper in the mid-span was conducted. The proportion of the steel beam segments and the damper was intended to mimic the mechanical properties of a prototype reinforced concrete (RC) coupling beam in a prototype 27-story building of RC frame-core dual system in a high seismicity region in China. The plan of the prototype building is 40.8 m long on both sides. The central core dimensions are 17.1m × 18.0 m. Twenty RC columns are arranged along the perimeter of the building. The 2.5 m long inner coupling beams above the elevator entrance in the middle stories (the 11 to 15 story) of the building are taken as the prototype for the design of the specimen. The cross section of the prototype coupling beam is 1.0 m in depth and 0.2 m in width. It is assumed that the concrete nominal compressive strength is 45 MPa and the section is symmetrically reinforced by HRB400 rebars (400MPa nominal yield strength) of a 1.2% tensile reinforcement ratio.

The strength of the prototype RC coupling beam is estimated according to the Chinese concrete codes. As a result, the shear strength of the coupling beam is governed by flexural strength of the RC cross section which is 745 kNm. The stiffness of the coupling beam is taken as 50% of its elastic stiffness to represent a cracked beam. The elastic stiffness takes into account both the flexural and shear deformation and is evaluated based on the gross cross section. The resultant strength and stiffness of the prototype coupling beam are 596 kN and 227 kN/mm, respectively.

3. Specimen and loading setup

The following criteria are followed in proportioning the mid-span friction damper and the steel shape segments on both sides of the damper: (1) The shear strength of the friction damper equals that of the RC coupling beam without considering any over-strength; (2) The stiffness of the steel coupling beam is similar to, or at least of the same order of magnitude of that of the RC coupling beam; (3) the steel shape segments adjoining the friction damper would not yield or become unstable.

In order to match the capacity of the loading facility, a 5/6-scale specimen of the above-mentioned steel coupling beam is designed and tested. The scaled strength and stiffness of the prototype RC beam becomes 596×(5/6)^2 = 414 (kN) and 227 × (5/6) = 189 (kN/mm), which are used as design targets for the specimen.

Figure 2 depicts the configuration and dimensions of the specimen. The loading frame of two girders and two pinned columns as shown in Figure 3 is used to impose shear to the coupling beam. Welded steel shapes are used for the adjoining steel shape segments on both sides of the friction damper. For the friction damper, four steel-to-brake pad friction interfaces are adopted and two ϕ30 high-strength bolts (Grade 10.9) are pre-tensioned to apply the required normal force on the friction interfaces. The brake pad is made of phenolic resin composite mixed with copper flakes, the recipe of which is held by the Yishexu Co. Ltd. A friction coefficient of 0.31 is presumed (which turns out to much higher than test values), resulting in a required pre-tension of 165.4 kN for each bolt to produce a target shear strength (total friction force) of 414 kN of the damper. A suite of eight disc springs of 160 mm diameter are placed in series with the friction interfaces to reduce the influence of any thermal strain that may develop during the loading on the magnitude of the normal force. The average pressure on the friction interface is about 8 MPa, which is estimated simply by dividing the pre-tensioning force of a single bolt by the area of the disc spring. It falls into the commonly used pressure range for friction dampers (that is 5 MPa to 15 MPa) in the passive control manual by Japan Society of Seismic Isolation. A load cell is installed in series with each set of the disc springs to monitor the normal force throughout the test.

Slots are made on one of the two sets of the steel ‘teeth’ (10 mm thick plates) that project from the end plates of the two steel shape segments and jacket the brake pads, while holes are made on the other set of the teeth. The dimensions of the slots determine the stroke of the damper in two ways. The length of the slot is 210 mm on both sides of the original bolt position so that the coupling beam can sustain about 10% chord rotation before the bolt is blocked by the upper or bottom edge of the slot. On the other hand, the width of the slot is 42 mm, which is 12 mm greater than the diameter of the bolt, to accommodate the longitudinal deformation of the damper at about 9% chord rotation of the coupling beam. Such longitudinal deformation is mainly a result of the departure of the two sets of steel teeth when they move along their own circular obits, assuming the overall length of the coupling beam remains unchanged. The above estimates on the limits of chord rotations neglect the deformation of the steel shape segments and the loading columns.

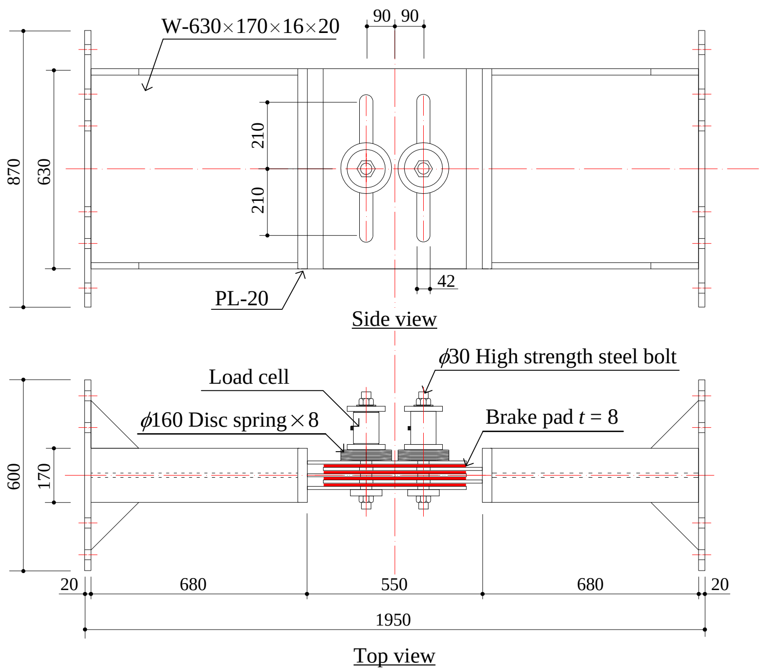

Fig. 2: Specimen of steel coupling beam with friction damper.

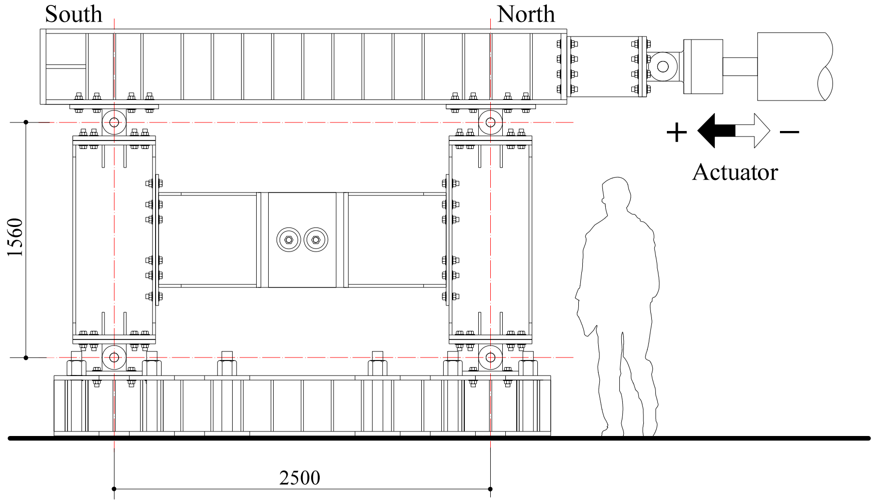

Fig. 3: Loading setup.

Six LVDTs are setup to monitor the transverse deformation of both the overall coupling beam and the friction damper. In particular, a pair of LVDTs is used to measure the diagonal changes of the coupling beam, which are denoted as δ_1 and δ_2 in Figure 4. The coupling beam chord rotation, θ_{CB},can then be evaluated by Equation 1. Another two pairs of LVDTs are installed to measure the vertical relative movements of the two pairs of steel teeth along the slots, denoted as δ_3 through δ_6. The lateral deformation of the friction damper, δ_{FD}, is calculated by Equation 2.

$$\theta_{CB} = \frac{(\delta_2 - \delta_1)\left(2\sqrt{a^2+e^2}+\delta_1+\delta_2\right)}{4ae} \quad (1)$$

where *a* and *e* are the depth and length of the coupling beam, respectively.

$$\delta_{FD} = \frac{(\delta_4 - \delta_3)+(\delta_6+\delta_5)}{2} \quad (2)$$

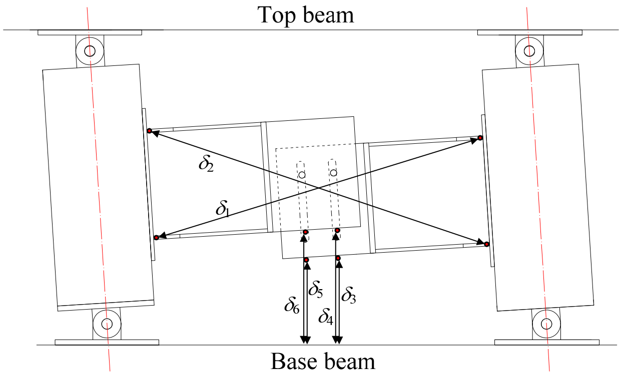

Fig. 4: Displacement measurement.

The specimen is first loaded to about half the shear strength of the friction damper for two cycles to measure the initial stiffness of the coupling beam. This is followed by a series of cyclic loading with monotonically increasing amplitudes of coupling beam chord rotation from 0.5%, 1%, 2%, 4%, 6% up to 8% (Phase 1). Two cycles are performed for each amplitude. Then 30 cycles with constant beam chord rotation of 4% are conducted to test the abrasion performance of the friction damper (Phase 2). Finally, the specimen is monotonically pushed towards the positive loading direction until the pre-tensioned bolts are blocked. Figure 5 depicts the full loading history.

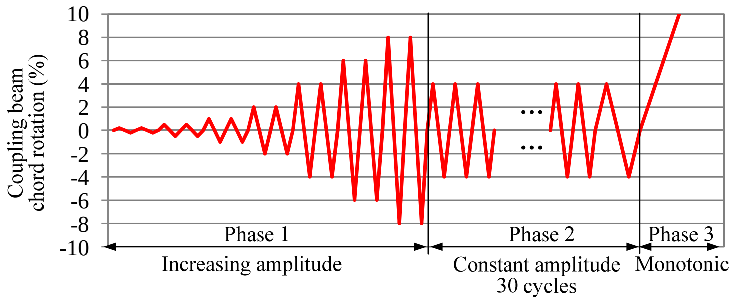

Fig. 5: Load protocol.

4. Results and discussions

During the first two cycles of loading in Phase 1, the friction pads have not started to slide and the initial stiffness of the coupling beam can be measured by connecting the peak deformation points on both sides of the hysteresis (Figure 6). The stiffness is measured to be 104 kN/mm, which is 55% of the stiffness of the scaled prototype RC coupling beam. At this stage, the deformation of the friction damper is very small and only constitutes less than 10% of the overall deformation of the coupling beam.

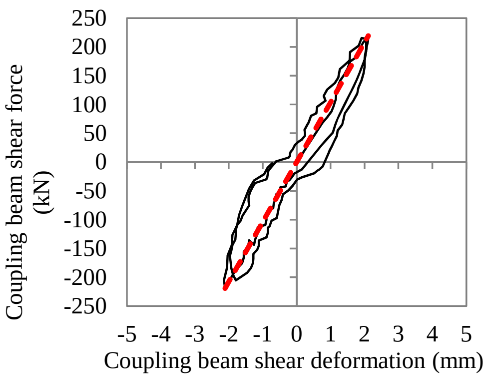

Fig. 6: Determination of initial stiffness of specimen

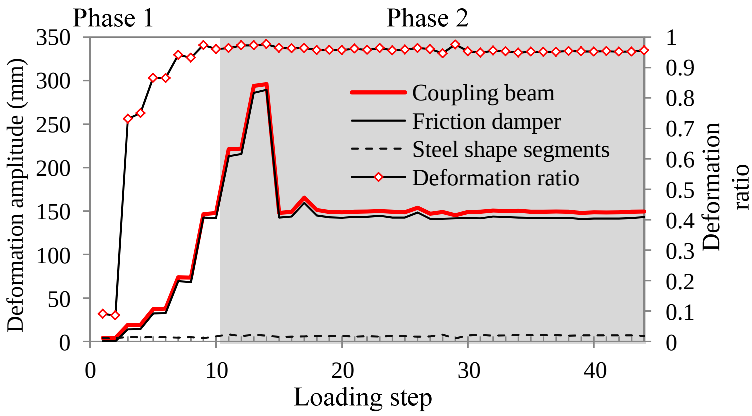

Fig. 7: Transvers deformation decomposition.

In the subsequent loading cycles, however, the friction damper starts to slide and its deformation increases rapidly while that of the steel shape segements remains almost the same. As a result, the ratio of the friction damper-to-coupling beam deformation rises to about 95% in Phase 2 loading, as is shown in Figure 7. In other words, the friction damper concentrates most of the deformation of the coupling beam.

Figure 8 shows the shear force ratio-shear deformation relationship of the friction damper in all the three loading phases. The damper shear force ratio is calculated by dividing the shear force of the damper by the normal force and the number of friction interfaces (i.e., 4 in the current case). The shear force is derived from the actuator output force by force equilibrium, and the normal force is monitored by the load cells in series with the friction interfaces. This ratio is practically the friction coefficient when the brake pad slides. The hysteresis is very stable even during the 30 cycles of constant amplitude loading in Phase 2. At the end of the loading there is a sudden increase in the shear force at 9.3% coupling beam chord rotation, indicating the contact of the bolt with the slot edges. The loading is terminated at 9.8% coupling beam chord rotation for safety concerns. Assuming the coupling beam chord rotation is 4 times the inter-story drift ratio of a coupled wall system, this corresponds to 2.4% drift ratio, which is greater than common allowable story drift for such lateral systems.

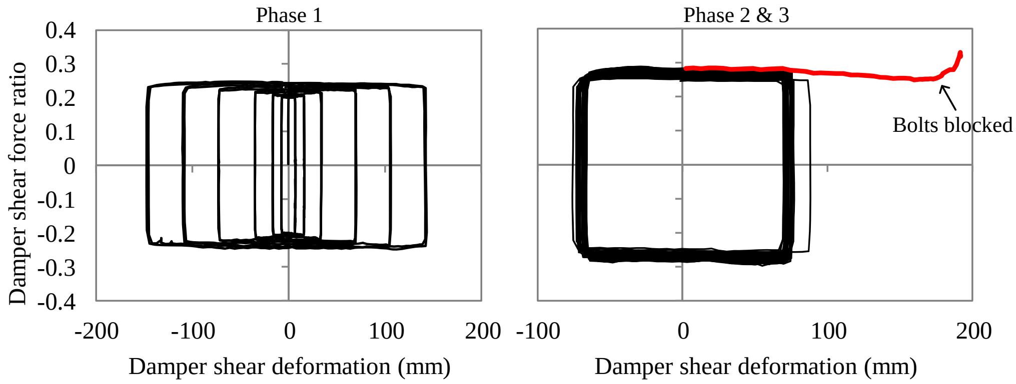

Fig. 8: Load-deformation hysteresis of friction damper.

The normal force provided by the pre-tensioned bolts tends to drop during the loading. In Phase 1, the bolts are re-fastened once the force drops to less 90% of the target force. This is, however, not conducted in Phase 2 and 3 to show how much the normal force would drop after 30 cycles of loading at large deformation. As a result, the bolts are re-fastened three times during Phase 1, as can be seen in Figure 9. In addition to the overall trend of relaxing, the normal force exhibits rise-and-drop cycles in small magnitude. In a loading cycle, the normal force tends to drop when the specimen is loaded towards the negative direction and recovers to some extent when it is reloaded towards the positive direction. The magnitude of such cyclic variation in normal force is about 6 kN, about 2% of the target force. Such variation may result from the fact that the thickness of steel teeth jacketing the brake pads is not perfectly constant so that they are squeezed harder to each other in one direction of loading and less hard in the other direction.

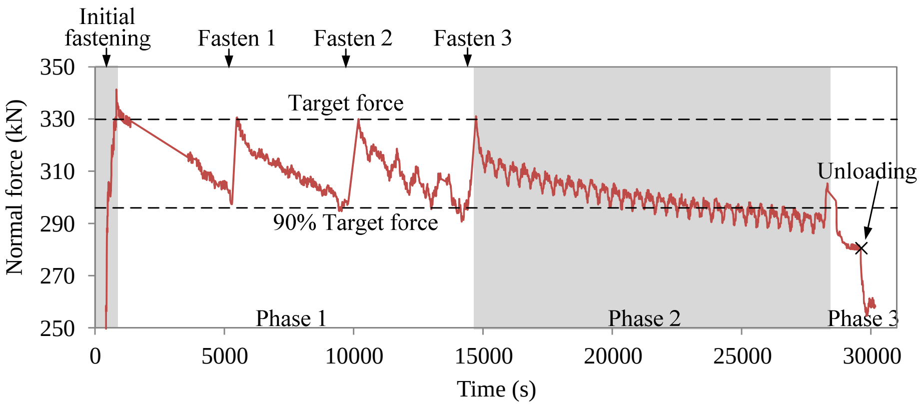

Fig. 9: Variation of normal force on the frictional interface.

Despite the relaxation of the normal force, the friction force of the damper gradually increases during the loading, although very slowly (Figure 10). Excluding the static friction at the beginning of Phase 1, the friction force increases from 252 kN to 312 kN at the end of Phase 1, that is, 24% over-strength. It continues to increase to 334 kN at the end of Phase 2, resulting in a 33% over-strength. At the same time, the kinematic friction coefficient of the friction interface constantly increases from 0.20 at the beginning of Phase 1 to 0.28 at the end of Phase 2. Such increase in friction coefficient may highly depend on the material of the brake pad and may be related to the increased temperature on the friction interface, which is unfortunately not monitored in the present test. Further test investigations with the temperature being monitored may provide insight into this problem.

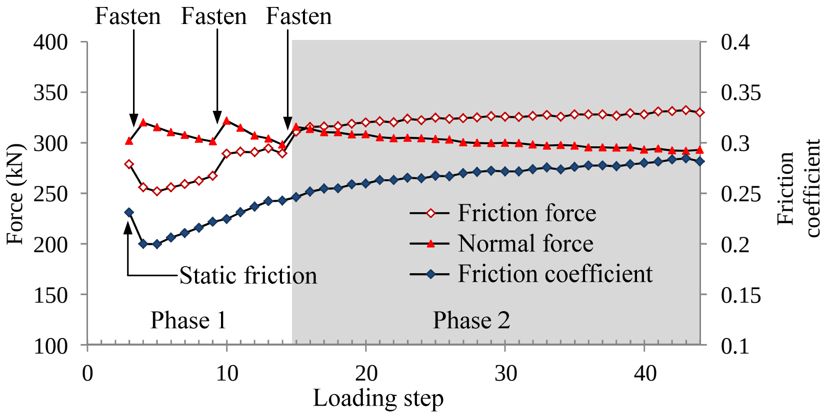

Fig. 10: Variation of friction coefficient of the brake pad-to-steel interface.

5. Summary

A friction damper is proposed and tested for the use in steel coupling beams in high-rise buildings. The preliminary test shows that the hysteresis of the friction damper is full and stable, indicating superior energy dissipating capacity. The easy-to-disassemble feature also makes it promising in terms of damage inspection and rapid recovery. However, the following issues remain problematic and deserve further investigations before such dampers can be implemented in realistic construction.

(1) The mechanism of the significant rise in friction coefficient needs to be carefully investigated in order to avoid or estimate the magnitude of such rise. It can become a major concern for practical design because the over-strength of the friction damper needs to be taken into account for proportioning the adjoining components.

(2) Mid-span friction dampers concentrate most of the deformation of the coupling beam. This concentration may impose significant deformation demand for the floor slab on the coupling beam if appropriate measures are not taken to protect the slab. Possible extent of damage to the slab due to such concentrated deformation and measures to mitigate such damage deserve further study.

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