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Dynamic response of structures with a friction-yield damper

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Dynamic response of structures with a friction-yield damper

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Abstract : In this study, the effects of an energy dissipation device in a reinforced concrete building are presented. The damper that is used in this study is part of the passive energy dissipation systems and absorbs the seismic energy through yielding in bending and frictional forces that occur in the metallic elements of the damper. The existence of this friction-yield damper : (i) increases the stiffness of the structure, (ii) absorbs seismic energy, (iii) and controls the axial forces occurring at the diagonal steel braces. The first step of this study is to present the dynamic response of this damper, testing it experimentally under cyclic loading. These experimental results have been compared to the finite element model of the damper results. In addition, a three-story reinforced concrete building is studied in this paper. It is being analysed using push-over and time history analysis, as regards three different cases, (i) the benchmark r/c building (BM3), (ii) the strengthening building with steel diagonal braces (DS3), and (iii) the strengthening building with the investigated damper (DS3-Damper). A comparison of the strengthening solution is presented and further useful results are observed.

1. Introduction

Nowadays, there is a huge variety of dampers that could be used to minimize the dynamic response of existing or new structures by absorbing the structural vibratory energy and dissipating it through their inherent hysteresis behavior, such as viscous dampers [1-3], metallic dampers [4-7], and friction dampers [8-11]. Some of the dampers are applicable in steel braces [12-13], others in base isolation [14-15] and an innovative technique is the inter-story isolation for high-rise buildings [16]. To prove the effectiveness of the dampers, they were studied in experimental research or numerical research and many review articles are presented [17-21].

In this study, the friction-yield damper absorbs the seismic energy by yielding bending and frictional forces that occur in the metallic elements of the damper [9, 22-24]. The first step of this study is to present the dynamic response of this damper, testing it experimentally under cyclic loading. These experimental results have been compared to the finite element model of the damper results. In addition, a three-story reinforced concrete building is studied in this paper. It is being analysed using push-over and time history analysis, as regards three different cases, (i) the benchmark r/c building (BM3), (ii) the strengthening building with steel diagonal braces (DS3), and (iii) the strengthening building with the investigated damper (DS3-Damper). A comparison of the strengthening solution is presented and further useful results are observed.



2. Response of the friction-yield damper

2.1. Experimental setup

The damper at full scale was experimentally investigated under cyclic loading [25]. The details of the experimental specimen are presented in Figure 1. The input load was controlled with a 200kN capacity load cell. The actuator was connected to a computer system that records its displacement, its load, the pressure of actuator oil, and its temperature, while one LVDT was positioned parallel to the longitudinal axis of the damper and measured the relative movement of the interior shaft to the exterior tube. All data were recorded and stored in a digital data system. Every group of superimposed blades consists of four steel blades, each 5mm thick with a tie shape. Quasi-static cyclic tests, with a rate of 3mm/minute, were carried out to ascertain the damper's capacity to absorb seismic energy.

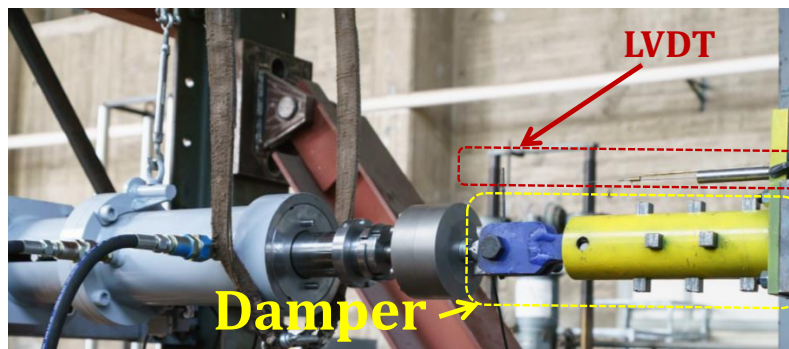


Figure 1. Experimental setup.

2.2. Results

Two sequences have been experimentally studied. The first sequence includes ten loading cycles (target load of 96kN and 120kN) to confirm the efficacy of the damper in maintaining its ability to absorb seismic energy under repeated cyclic loading (Figure 2). The second sequence is based on the ATC-24 protocol [26]. The ATC-24 charge protocol uses the yielding displacement as a reference point for increasing the intensity during loading cycles. More specifically, the first six cycles are elastic, followed by three cycles with a reference point shift, three cycles with a double reference point shift, three with a triple reference point shift, two with a quadruple shift, and finally two with a quintuple shift.

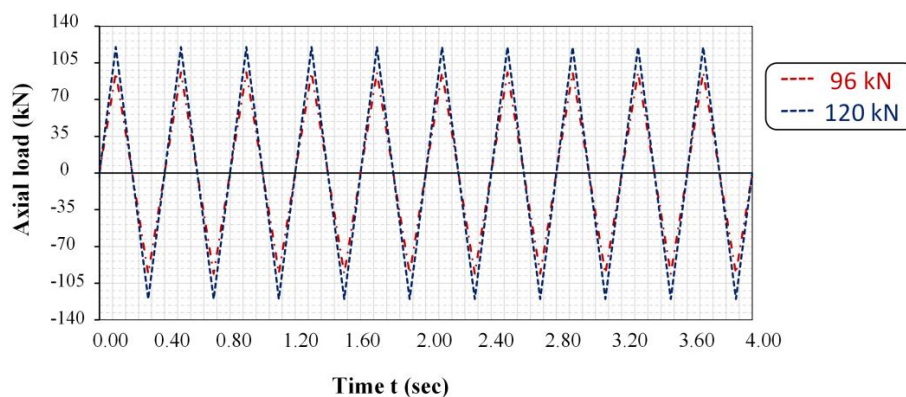


Figure 2. Time history load of the first sequence.

Figures 3 and 4 show the hysteresis loops that emerged from the experimental sequences. The area inside a hysteresis loop represents the seismic energy that the damper dissipates. It is noticed that both the shape and the consistency of the hysteresis loops remain constant during the repeated cycles, which proves that the damper is effective in dissipating seismic energy whereas it will not lose its efficacy during the repeated cyclic load.

Figure 3 presents the hysteresis loops of the first sequence, the target load of 96kN is indicated with a red line, and the target load of 120kN is indicated with a blue line. Figure 4 shows the hysteresis loops of the second experimental sequence (based on loading protocol) with a red line, while the black line presents the results of the respective finite element model (FEM) analyses from previous research of the same author [9].

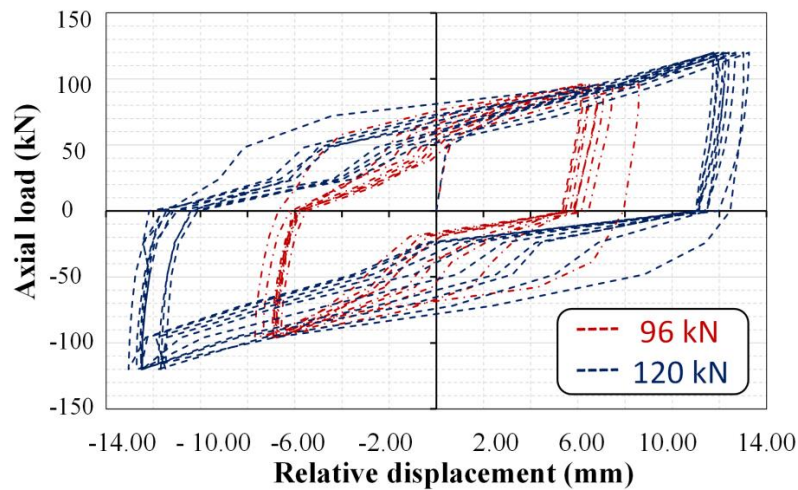


Figure 3. Comparison of ATC-24 load protocol hysteresis loops and FEM monotonic curve.

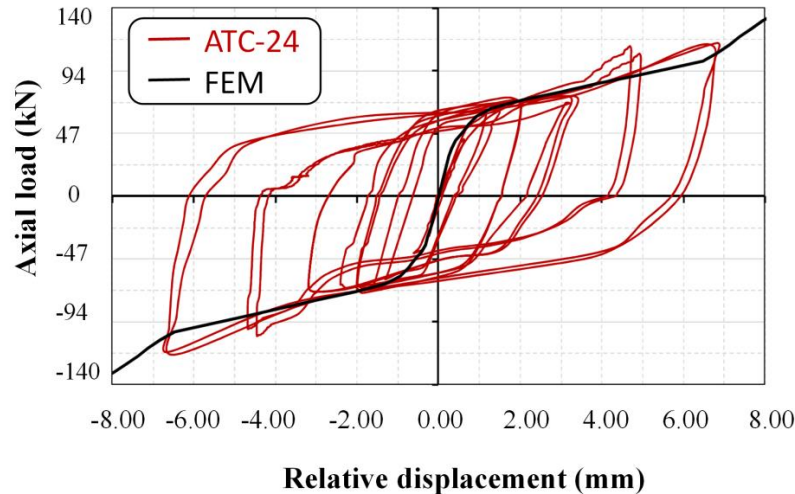


Figure 4. Comparison of ATC-24 load protocol hysteresis loops and FEM monotonic curve.

From the shape and range of the hysteresis loops, as illustrated in Figure 4, it is noticed that the arrangement complies with the global anti-earthquake requirements design since it absorbs a large part of the seismic energy. In addition, the monotonic load-displacement curve can be reliably used to evaluate its stiffness and strength of the investigated damper.

3. Dynamic response of a three-story building

The investigated three-story building, BM3, is plane and it is illustrated in Figure 5. The longitudinal dimension is 25.00 m and it consists of five frames. The height of each floor is 3.00m. The concrete that

was used is class C16/20 ($f_{ck} = 16 \text{ MPa}$, $E_{cm} = 28608 \text{ MPa}$), the steel of the longitudinal steel bars is STIII (\approx S400, with min. yielding strength $f_{yk} = 400 \text{ MPa}$, min. ultimate strength $f_{su} = 500 \text{ MPa}$ and min. fracture strain $\varepsilon_{su} = 12\%$) and the steel of the transverse steel bars is STI (\approx S220, with $f_{yk} = 220 \text{ MPa}$, $f_{su} = 340 \text{ MPa}$, and $\varepsilon_{su} = 18\%$). The dimensions of the columns of the ground and first floor are $0.45 \times 0.45 \text{ m}$, and those of the last floor are $0.40 \times 0.40 \text{ m}$. The beams of the ground and first floor are $0.25 \times 0.50 \text{ m}$, and those of the last floor are $0.25 \times 0.40 \text{ m}$. The thickness of the floor slab is equal to 0.15 m .

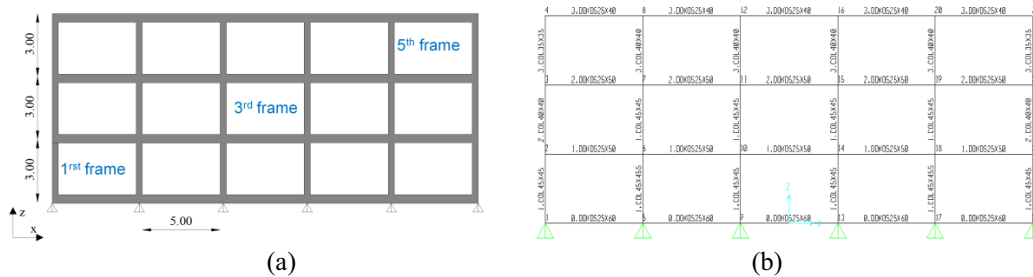


Figure 5. (a) Description of the investigated three-story building (values in m), (b) finite element modeling of the same frame building.

The building is modeled as a two-dimensional frame with a rigid base at the foundation level, while columns and beams as nonlinear frame elements with rectangular cross-sections (as presented above) by using concentrated flexural (M3) and axial load-flexural (P-M3) plastic hinges, respectively, to both ends. Hinge properties are defined through the definition of the moment–curvature relation determined under the following FEMA-356 [27]. The building is subjected to gravity and lateral loads.

This section presents and compares the use of the friction-yield damper in steel diagonal braces to seismic retrofit the BM3 building. The retrofitting solutions are: i) the use of steel diagonal braces (DS3), and ii) the installation of the damper in the steel diagonal braces (DS3-Damper), as illustrated in Figure 6.

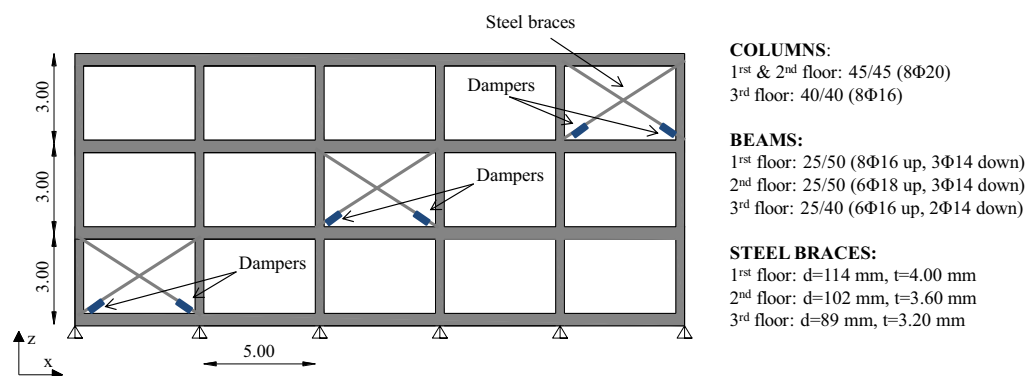


Figure 6. Description of the DS3-Damper building.

3.1. Push-over analysis

A nonlinear static pushover analysis following the ATC-40 [28] procedures is performed to assess the performance of the framed building under two different levels of shaking (“Life Safety” and “Collapse”). A floor displacement drift of 1.6% corresponds to a seismic performance level of “Life Safety” ($drift = 1.6\%$), and a drift of 2.1% corresponds to a seismic performance level of “Collapse”

(*drift* = 2.1%) [13]. We have chosen a relative floor displacement equal to 2% for our construction. Therefore, the relative displacement for each floor is equal to $2\% \cdot 3\text{ m} = 6\text{ cm}$, which gives a total displacement at the top of the building of 18.00cm. Pushover curves of all buildings (BM3, DS3, and DS3-Damper) are compared in Figure 7. It is noticed that the DS3-Damper building is able to take a 201% (1810 kN) higher base shear load compared with the BM3 building for the same level of displacement (*drift*=2%). Although the building DS3 is able to achieve 156% (1490 kN) higher base shear load compared with the BM3 building for the same level of displacement (*drift*=2%), we can notice the buckling of the steel diagonal braces of the last floor and also the collapse of the columns of this floor (Figure 8).

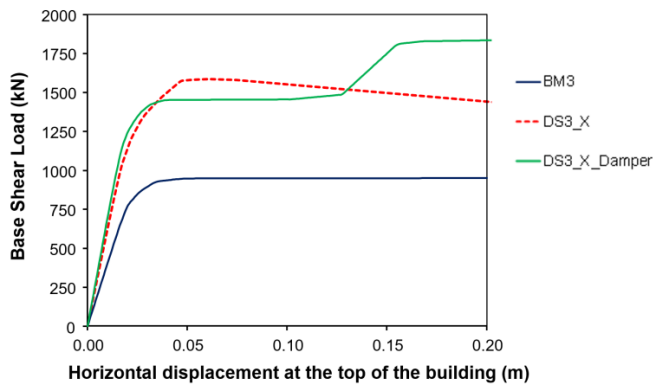


Figure 7 . Comparison of the pushover curves.

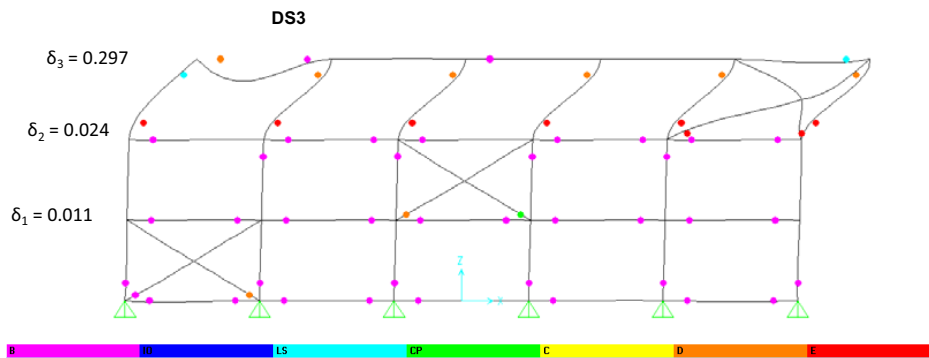


Figure 8. Plastic hinges of redesign building DS3 for a displacement level of 2 cm (at the first floor) that occurs the collapse of the last floor.

Figure 9 presents the plastic hinges of RD3-Damper for a horizontal displacement at the top of the building of 18.0 cm. The hinges of the columns remain in the Life Safety (LS) performance level, so the building has not suffered substantial damage as a result of this horizontal displacement. In addition, with the installation of the friction-yield damper, the buckling of the steel diagonal braces was prevented.

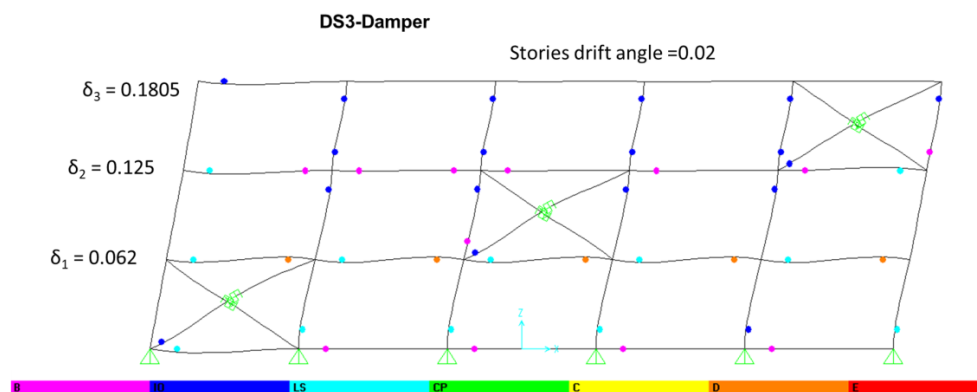


Figure 9. Plastic hinges of redesign building DS3-Damper for a displacement level of 18 cm (at the top of the building).

3.2. Non-linear time-history analysis

In this section, the result of a non-linear time history analysis is presented. A direct integration method, known as the β -Newmark, was used. Mass and stiffness proportional damping was chosen and critical damping ratios equal to 5% and 4% were considered for the first and the second periods of the analyzed buildings respectively. In Figure 10 the cycling shear base load versus time, for which the time history analyses were performed, is presented. The total duration of the time history input is equal to 20sec.

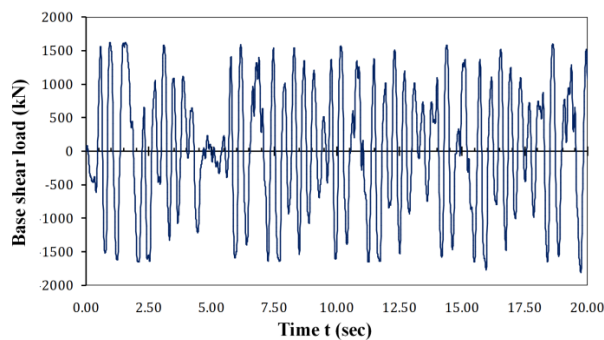
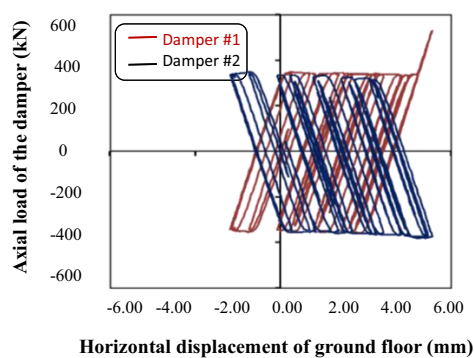
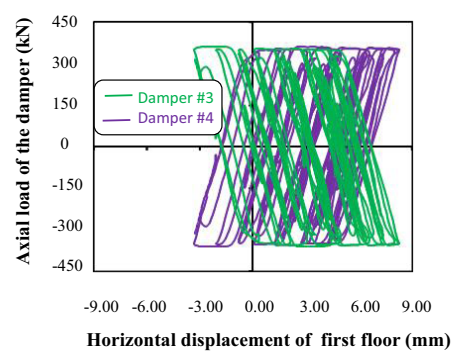


Figure 10 . Time history diagram of base shear load.

Figure 11 presents the hysteresis loops of the six dampers placed at the DS3-Damper building. These results confirm the main conclusion of the experimental study and the capacity of this damper to absorb seismic energy during repeated cycling loading.



(a)



(b)

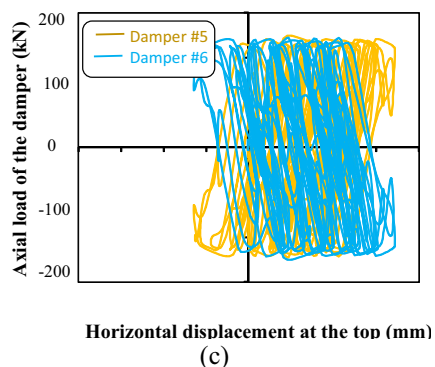


Figure 11 . Hysteretic loops : (a) dampers of the ground floor, (b) dampers of the first floor, (c) dampers of the last floor.

4. Conclusions

This study presents the results of an energy dissipation device installed in a reinforced concrete structure. The damper utilized in this investigation is a component of passive energy dissipation systems, and it absorbs seismic energy by bending and frictional forces in the damper's steel superimposed blades. This friction-yield damper's presence improves the structure's stiffness, absorbs seismic energy, and regulates the axial forces at the diagonal steel bracing. This study's initial phase involves presenting the damper's dynamic response and conducting an experimental test under cyclic loading. The finite element model of the damper results has been compared with the previous experimental findings. This research also examines a three-story reinforced concrete structure. In three distinct cases—the benchmark r/c building (BM3), the strengthening building with steel diagonal bracing (DS3), and the strengthening building with the researched damper (DS3-Damper)—it is being analyzed utilizing push-over and time history analysis.

A comparison of the strengthening solutions is presented, and the following conclusions are drawn:

- During the experimental setup, two sequences have been studied. The first one includes ten loading cycles (target load of 96kN and 120kN) and it confirms the efficacy of the damper to maintain its ability to absorb seismic energy under repeated cyclic loading (Figure 3). The second one is based on the ATC-24 protocol. Based on these results, from the shape and range of the hysteresis loops, as illustrated in Figure 4, it is noticed that the arrangement complies with the global anti-earthquake requirements design since it absorbs a large part of the seismic energy. In addition, the monotonic load-displacement curve can be reliably used to evaluate its stiffness and strength of the investigated damper.
- From the pushover curves of all buildings (BM3, DS3, and DS3-Damper), it is noticed that the DS3-Damper building is able to take a 201% (1810 kN) higher base shear load compared with the BM3 building for the same level of displacement (drift=2%). Although the building DS3 is able to achieve 156% (1490 kN) higher base shear load compared with the BM3 building for the same level of displacement (drift=2%), we can notice the buckling of the steel diagonal braces of the last floor and also the collapse of the columns of this floor (Figure 8).

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