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Chan, R., & Zhao, Z. (2012). Mitigation of seismic risks to soft-storey structures using toggle-brace-damper systems. *Applied Mechanics and Materials*, 238, 833–837.

<https://doi.org/10.4028/www.scientific.net/AMM.238.833>

Document Version: Accepted Manuscript

Published Version: <https://doi.org/10.4028/www.scientific.net/AMM.238.833>

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Citation:

Chan, R and Zhao, Z 2012, 'Mitigation of seismic risks to soft-storey structures using toggle-brace-damper systems', *Applied Mechanics and Materials*, vol. 238, pp. 833-837.

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Mitigation of seismic risks to soft-storey structures using toggle-brace-damper systems

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Keywords: earthquake, soft-storey, toggle, passive energy dissipation.

Abstract. Soft-storey mechanism is characterized by a sudden reduction of lateral stiffness in one or more levels of a structure. Soft-storey is often observed in the ground level due to the absence of wall or cladding. With recent develop of energy dissipation systems, soft-storey mechanism can be corrected by addition of a damper-brace assembly. In particular, this paper investigates the effect of toggle-damper-brace systems on such situations. Governing equations including the magnification factor and lateral stiffness contributed by a toggle-damper-brace are formulated. It was found that a toggle-damper-brace system, if proportioned correctly, will significantly increase the travel in the damper and overall stiffness of structure can be enhanced. An illustrative example is presented using nonlinear time history analysis implemented on MATLAB.

Introduction

In the last few decades significant research and development has been made to make civil structures safer and more robust in the event of an earthquake. Since 1990's, rapid increase in implementation of energy dissipating systems have been reported [1]. In this technique designated energy dissipating devices (EDD) are installed in the structure such that a portion of the energy originated from ground shaking is diverted to. Among many energy dissipation mechanisms, metallic yielding is the most popular mechanism. They belong to the class of displacement-based device, which relies on relative displacement which the device travels. Metallic based EDD is generally inexpensive, insensitive to frequency of vibration, and require minimal maintenance. EDD which make use of such mechanism include the patented ADAS [2], its variants TADAS [3] and the Steel Slit Damper [4]. The Buckling-restrained brace (BRB) [5] and its variant Buckling-restrained lug [6], on the other hand, makes use of the axial deformation of steel. Shear yielding of thin steel plates have also been used to dissipate energy through displacement [7].

On the other hand, a very widespread structural problem is characterized by the absence of claddings or walls at the ground floor while they are present in upper levels. It causes a sudden reduce in stiffness in the ground level. It's commonly termed "soft-storey". This configuration permits good use of the ground floor space, but in structural point of view it is undesirable. Large lateral load may cause significant rotation ductility demand at the extreme sections of the columns of the first storey, while the superstructure behaves like a quasi-rigid body (Fig 1). Soft-storey failure is commonly observed in earthquake damages, claiming significant life and economical losses. Conventional strengthening approach often involves addition of braces to ground level such that the lateral stiffness is increased. In this approach, however, the braces occupy the spaces disturb normal use of the space, such as car parks or retail space, etc.

Fig 1 Soft-storey mechanism

Toggle-brace-damper system

The main purpose to connect a damper to a toggle-brace is to magnify the displacement travelled in a damper. The configuration has been investigated by a number of researchers [8-9] and application in the US has been reported [8]. An upper toggle configuration presented in this paper is shown in Fig 2(a). Consider a single storey frame of dimension $h \times b$, the configuration is characterised by a lower brace of length l_1 , and an upper brace of length l_2 . The lower brace forms an angle θ with respect to the ground. To maximize usable floor space, we shall limit our study with θ greater than 45 degrees. For a given building dimension, geometry is completely defined by l_1 and θ . The damper is supported between the eave and toggle brace intersection O . Upon horizontal displacement of u in the superstructure (Fig 2b), the lower brace undergoes a rotation ϕ together with the change in position of brace intersection O to O' . It will cause an axial deformation of damper. In this regard, displacement-based passive energy dissipater which operates in axial movement will be suitable, for example the Buckling-restrained Lug [7] which relies on plastic deformation of a steel bar under axial movement. Generally, benefits of toggle-brace-damper system include:

1. Damper increases effective damping of structure, hence it suppresses vibration magnitude and base shears;
2. The toggle arrangement magnifies damper travel; and
3. The toggle arrangement maximizes usable space which is architecturally attractive.

Figure 2 The Toggle-Brace-Damper configuration

Magnification factor

Consider Fig2(b), due to ground shaking the superstructure is displaced by u . Assuming the brace elements are axially stiff, the position of O' can be determined by the intersections of the two arcs of radii of l_1 and l_2 . The change in damper length u_D can then be determined. The magnification factor f is defined as the ratio between the change in damper length and the horizontal displacement superstructure with respect to the ground, i.e.

$$f = \frac{u_D}{u} \quad (1)$$

The magnification factor varies with the magnitude of u , and it is affected by the geometry h , b , l_1 and θ . While h and b is determined by building geometry, l_1 and θ can be chosen by engineers. Fig 3 shows the magnification factor as a function of u for a number of l_1 and θ combinations.

Generally f increases as θ decreases. Also, it can be observed that f is fairly constant over practical ranges of displacement, although it tends to increase slightly with increase in displacement. It should be noted that for values of f less than 1.0, it indicates the toggle-brace configuration reduces damper travel, which is contrary to our requirement.

Fig 3 Magnification factor

To study the effect of toggle brace in lateral stiffness of system, let us consider the force exerted on the damper is F_D while the horizontal shear force on superstructure is V . If we assume the pinned beam-to-column joints, and assuming the brace members are axially rigid, all lateral stiffness is contributed by the damper. By equating external and internal work we have,

$$F_D u_D = V u \quad (2)$$

Overall horizontal stiffness of structure can be written as,

$$k = \frac{V}{u} \quad (3)$$

Substituting Eq. 1 in Eq. 3, and using damper stiffness $k_D = \frac{F_D}{u_D}$ we have,

$$k = \frac{V}{u} = \frac{F_D u_D}{u^2} = k_D \left(\frac{u_D}{u} \right)^2 = k_D f^2 \quad (4)$$

As a result the magnification factor has an effect on horizontal stiffness of structure. For a frame with inherent lateral stiffness k_s , such as for moment-resisting frames, the total horizontal stiffness after addition of a toggle-damper brace system can be expressed as numerical summation of stiffness, i.e.

$$k_{tot} = k_s + k \quad (5)$$

k_s denotes lateral stiffness of parent frame prior to addition of brace and device. Post-yield stiffness ratio α after yielding of damper is given by,

$$\alpha = \frac{k_s}{k_{tot}} = \frac{k_s}{k_s + k_D f^2} \quad (6)$$

α is an indication of stiffness contribution by the toggle-damper brace. When α approaches infinity it indicates an infinitely stiff toggle-damper brace. Yield displacement of complete system u_y equals u_D / f . Yield strength of the system with a toggle-damper assembly added is expressed as

$$P_y = k_{tot} u_y = \frac{k_s u_D}{\alpha f} \quad (7)$$

Consequently, the nonlinear behaviour of a structure installed with toggle-brace-damper system is completely defined by four parameters: k_s , f , α and u_D . In practice, k_s of the building can be estimated by structural analysis, whereas f and u_D are choices of the designer.

To model nonlinearity of dampers, a continuous Bouc-Wen's model [10] is adopted in this study. A single equation governs both elastic and inelastic range of the device under cyclic loading. Resilient force of complete system $P(t)$ is expressed by,

$$P(t) = \alpha k_{tot} u(t) + (1 - \alpha) k_{tot} u_y z(t) \quad (8)$$

where α and k are defined previously, γ , β and n are calibration parameters, and $z(t)$ is a variable contains hysteretic properties, which is defined by a first-order nonlinear differential equation,

$$u_y z(t) + \gamma |\dot{u}(t)| z(t) |z(t)|^{n-1} + \beta \dot{u}(t) |z(t)|^n - \dot{u}(t) = 0 \quad (9)$$

Numerical example

To illustrate the effect of toggle damper-brace systems, consider an existing building that suffers from soft-storey mechanism as shown in Fig 4. This building is to be retrofitted by installing toggle damper-braces in the ground level. The superstructure weighs 600tons, which is elevated by 3.5m from the ground by 16 steel columns (200UC46.2). Lateral stiffness of structure prior to addition of braces is estimated to 41.1kN/mm. The structure is to be retrofitted by adding 4 toggle-damper braces, with 2.0m long lower brace at an angle of 45° from horizontal. This configuration results in a magnification factor f of approximately 2.0. By using a damper with axial stiffness of 5.2kN/mm, the overall stiffness of structure is increased, achieving an α value of 0.33. Table 1 shows the parameters used.

Fig 4 Example soft-storey structure

Table 1

M	k_s	ζ	l_l	θ	f	k_D	u_D	α
600kNs ² /m	41.1kN/mm	3%	2.0m	45°	2.0	5.2kN/mm	3.5mm	0.33

For illustrative purpose, a single direction ground motion is applied. The input ground shaking is an un-scaled N-S component of 1940 El Centro Earthquake obtained from PEER Strong Motion Database [11]. Eqn 8 and 9 are implemented by numerical integration on MATLAB, the differential equations are solved using 4th order Runge-Kutta algorithm (MATLAB command ode45).

Fig 5(a) shows the base shear plot. The nonlinearity of base shear is a consequence of nonlinear damper. Fig 5(b) shows the cumulative energy diagram. At the end of ground shaking, approximately 79% of input energy is diverted to the damper, while the remaining energy is dissipated through viscous damping. Maximum displacement of superstructure is controlled within 23mm (1/152 of height of columns).

Fig 5 (a) Base shear plot and (b) Cumulative energy dissipation

Summary

Soft-storey mechanism is a common problem observed in many historical earthquake events. It is characterized by a “soft-storey” which the horizontal stiffness of a particular storey is significantly smaller than the rest of the structure. When a strong earthquake hits the large shear force exerted on superstructure causes plastic rotations in columns, subsequently causes collapse of the soft-storey. This paper investigates the use of toggle-damper-brace system as a mitigation measure to soft-storey buildings. Governing equations of such system are presented in this paper. . It was found that a toggle-damper-brace system, if proportioned correctly, will significantly increase the travel in the

damper and overall stiffness of structure can be enhanced. A numerical example of a single storey structure retrofitted by addition of toggle-damper-braces is presented.

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