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Design principles for stiffness-tandem energy dissipation coupling beam

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Abstract. Reinforced concrete shear wall is one of the most common structural forms for high-rise buildings, and seismic energy dissipation techniques, which are effective means to control structural vibration response, are being increasingly used in engineering. Reinforced concrete-mild steel damper stiffness-tandem energy dissipation coupling beams are a new technology being gradually adopted by more construction projects since being proposed. Research on this technology is somewhat deficient, and this paper investigates design principles and methods for two types of mild steel dampers commonly used for energy dissipation coupling beams. Based on the conception design of R.C. shear wall structure and mechanics principle, the basic design theories and analytic expressions for the related optimization parameters of dampers at elastic stage, yield stage, and limit state are derived. The outcomes provide technical support and reference for application and promotion of reinforced concrete-mild steel damper stiffness-tandem energy dissipation coupling beam in engineering practice.

Keywords: shear wall; seismic energy dissipation; mild steel damper; coupling beam

1. Introduction

Reinforced concrete (RC) shear wall structures are characterized by high land utilization and excellent lateral stiffness, and are widely used in residential, office and advanced hotel buildings (Hemsas *et al*. 2014, Saad *et al*. 2016). However, there have been a number of recent cases of damaged shear wall buildings in large earthquakes, such as in Chile and Wenchuan (Liang *et al*. 2009, Zhou and Lu 2011). Therefore, improving shear wall seismic resistance has become a crucial research focus.

Reinforced concrete coupling beams (RCCBs) are important components of RC shear walls, frame shear walls, and tube structures. These mainly have the role of passing the shear force to main components at both ends of the beam, such as shear walls or frame columns (Paulay and Priestley 1992). Coupling beam stiffness, deformation, and capacity affect the lateral stiffness, bearing capacity, and ductility of the whole structure (Fang 1985).

It can be derived from Eqs. (1) and (4) that the proportion of shear deformation in the coupling beam mid-span displacement will exceed 10% if the ratio of beam span to depth is less than 5. Thus, the coupling beam is subjected to diagonal tension failure caused by insufficient stirrup, and shear sliding failure at both ends due to cohesion failure between longitudinal reinforcement and the concrete (Paulay and Binney 1974). These are brittle failure modes due to the lack of shear bearing capacity in the components. However, coupling beams are the first anti-seismic line of defense for the structure, and are designed to neither yield too early nor to have excessive beam stiffness. Early yield will cause insufficient function in normal use and small earthquakes, and excessive beam stiffness and bearing capacity fails the design principle of strong shear wall with weak coupling beams. Therefore, considerable research within China and elsewhere has been conducted on seismic design of coupling beams after the Alaska earthquake in 1964, and many designs have been proposed, such as diagonally reinforced, oblique cross steel, diamond reinforced coupling, concrete-steel composite, rigid, and stiffness-tandem energy dissipation coupling beams (Nestorović *et al*. 2015, Tegos and Penelis 1998, Bengar and Aski 2016).

Stiffness-tandem energy dissipation coupling beams are designed on the basis of energy dissipation theory and component function, and can enhance the beam’s anti-seismic role.

This article investigates the design principles and equations for mild steel dampers based on current research status and known deficiencies of reinforced concrete-mild steel damper stiffness-tandem energy dissipation (RC-MSDS-TED) coupling beams.

2. Research status of RC-MSDS-TED coupling beams

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Since 1990s, considerable research and application has focused on RC-MSDS-TED coupling beams. Li (1992) proposed a new type of shear wall design, installing a friction control device mid-span of the coupling beam. The proposed design has been shown to have superior seismic performance compared with conventional designs.

Yukinobu *et al*. (2002) designed an energy dissipation coupling beam by means of truncating the mid-span concrete and exposing the profile steel. Quasi-static loading tests showed this design scheme had superior energy performance, and the beam had been applied in a variety of Japan construction engineering (Hitoshi 2010). However, the coupling beam is difficult to repair and replace once it’s damaged because the profile steel, which acts as a damper, is embedded in RC at each end of the coupling beam.

Fortney *et al*. (2007) proposed a design with a replaceable "fuse" in the coupling beam, i.e., installing weakened thickness joist steel in the role of a fuse. The fuse yields easier than the RC coupling beam, and can be easily changed after it is damaged.

Duan (2011) applied the technology of RC-MSDS-TED coupling beams to the first "national earthquake safe community" in Yongjia Shangpin Tiancheng, Dalian city, China. They employed mild steel dampers with easy maintenance and replacement, being connected to the RC by bolts.

Mao *et al*. (2012) proposed a coupling beam design using a shape memory alloy (SMA) damper, which provided good self-resetting capability. SMA stiffness is smaller, with larger ductility (Heresi *et al*. 2014), than previous materials used as dampers, so this type of damper effectively protected the RC ends from damage. However, SMA dampers are somewhat more expensive, which has limited their engineering applications.

Chao and Dagen (2012) analyzed damping mechanisms and mechanics performance of RC-MSDS-TED coupling beams. They proposed design formulas for the energy dissipated by coupling beams and calculation methods for damper vertical distribution structure patterns with control targets being displacement ductility coefficient, coupling ratio, and equivalent damping ratio in the damper.

Li (2013) analyzed truncating and installing mild steel dampers in RC coupling beams. Based on the demand of vibration attenuation in the structure, they proposed a stiffness control principle and design method for mild steel dampers.

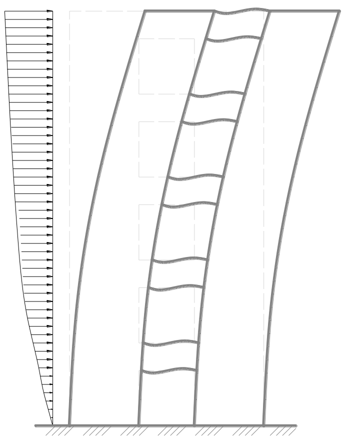
Although RC-MSDS-TED coupling beams have been applied in some engineering projects, the relevant research remains immature. In particular, there has been little research on the specific relationship between the spatial distribution of dampers on structural and damping effects.

Energy dissipation induced by damper spatial distribution is mainly reflected in three aspects. Step 1: under the condition of the energy dissipation capacity of the whole structure having been evaluated, how to determine the influences of energy absorption from the multiple dampers in the structural height direction, i.e., how many dampers should be fixed on each floor to achieve optimum energy absorption. Step 2: damper design to achieve optimum energy dissipation considering the synergy between the damper and the RC beam, i.e., how to optimize overall performance at the structure level by controlling damper mechanical parameters. Step 3: determine the connection structural measures between damper and reinforced concrete beam, and adopt anti-fire as well as anti-corrosion measures to dampers. There are corresponding and complementary relationships among the steps.

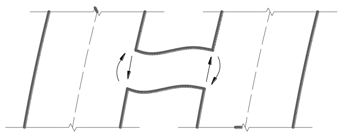
This paper focused on method and theory to solve the step 2 problem, with step 1 and step 3 problems to be addressed in further research.

3. Design principles for a metal damper

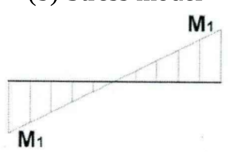
The shear wall in lateral load is mainly characterized by bending deformation, as shown in Fig. 1(a). Under bending deformation, the bending moment of the coupling beam is asymmetric, bending moment at mid-span is zero, and shear force is uniformly distributed along the length of the beam. Deformation, bending moment, and shear force of a coupling beam under lateral load are shown in Figs. 1(b)-1(d), respectively.



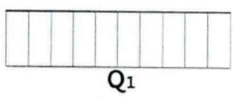
(a) Structure deformation



(b) Stress model



(c) Bending moment



(d) Shear force

Fig. 1 Stress diagrams for reinforced concrete shear wall structure

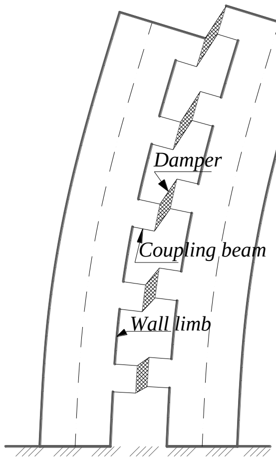
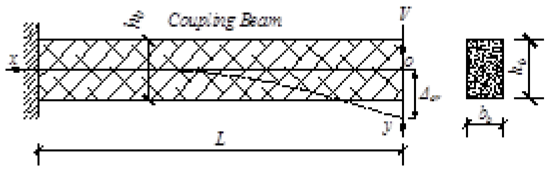
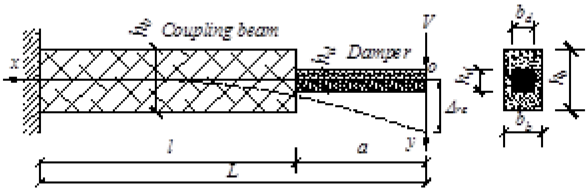


Fig. 2 Energy dissipation beam



(a) Original beam structure



(b) Energy dissipation coupling beam with damper installed

Fig. 3 Concept diagram of beam components

The shear direction of a coupling beam differs with reciprocating load. Since the coupling beam has larger nonlinear displacement than the wall, it is exposed to shear failure under the strong ground motion of an earthquake. In seismic design, to achieve anti-seismic targets and meet energy dissipation requirements, the coupling shear wall must be designed according to the principle of strong wall with weak coupling beam, and the coupling beam designed according to the principle of strong shear with weak bending.

The coupling beam mechanical characteristics of minimal bending moment and maximum mid-span displacement in earthquakes, means the coupling beam often endures shear failure in an earthquake, and is not easy to repair once damaged. Therefore, the coupling beam can be truncated and mild steel dampers set at mid-span to consume the earthquake energy rather than the RC beam. This is a reinforced concrete-mild steel damper stiffness-tandem energy dissipation coupling beam, and the working diagram is shown in Fig. 2.

Size, stiffness, and strength of the metal damper must be carefully designed to ensure the working mechanism and seismic fortification roles are fulfilled under the guidance of established operation. When designing the metal damper, the following principles must be considered.

- The damper should have sufficient initial stiffness, so that the overall beam remains elastic under normal use and minor earthquake conditions.
- Control the failure mode and implement the concept of multi-channel seismic fortification to ensure the damper yields prior to the RC ends, and the composite coupling beam yields prior to the wall under moderate or major earthquake conditions.
- Control the bearing capacity of the dampers to ensure the maximum damper displacement under the limit load is not greater than the elastic-plastic drift ratio required by building codes, guaranteeing the damper has long fatigue life and sufficient energy dissipation without fatigue damage under earthquake loads.

3.1 Initial stiffness

Meeting the demand of initial stiffness of the structure mainly requires controlling deformation of the structure in the elastic stage. That is, ensuring the installed damper vibration displacement of the coupling beam is within an acceptable range under the required load.

Fig. 3 shows the calculation diagram for a coupling beam under common stress conditions, where L is half the length of the original beam structure, l is the length of RC after the beam is truncated, and a is half the length of the damper.

From material mechanics, beam displacements caused by shear and bending deformation in Fig. 3 are

$$\Delta_V = \frac{kVL}{GA} \quad \text{and} \quad \Delta_M = \frac{VL^3}{3E_b I_b} \tag{1}$$

Respectively, where $E_b I_b$ is the bending stiffness of RC beam; k=1.2 is the uneven distribution coefficient of shear force for rectangular section, I is the second moment of area, A is the area of the rectangular section, and

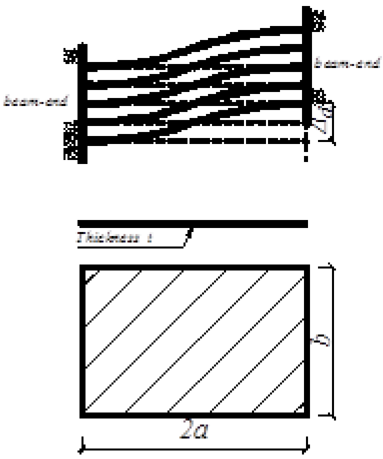
$$\frac{I}{A} = \frac{\frac{Ah_b^2}{12}}{A} = \frac{h_b^2}{12} \tag{2}$$

Where h_b is the cross section height of the coupling beam; G=0.4E is the shear modulus of the components; and the beam span-depth ratio is λ=2L/h_b. From Eq. (1), the displacement ratio between shear and bending deformation is

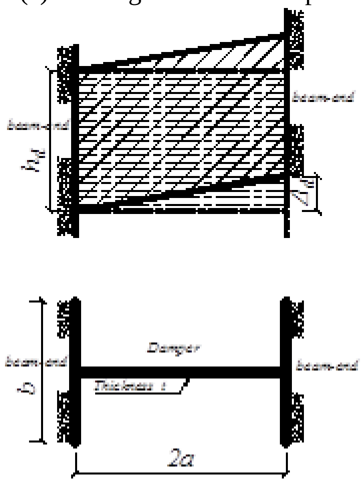
$$\frac{\Delta_V}{\Delta_M} = \frac{3h_b^2}{4L^2} = 3\Bigg/\left(\frac{2L}{h_b}\right)^2 = \frac{3}{\lambda^2} \tag{3}$$

And the maximum elastic displacement of the original coupling beam is

$$\Delta_{or} = \Delta_V + \Delta_M = \Delta_M\left(1 + \frac{3h_b^2}{4L^2}\right) = \frac{VL^3}{3E_b I_b}\left(1 + \frac{3}{\lambda^2}\right) \tag{4}$$



(a) bending mild steel dampers



(b) shear mild steel dampers

Fig. 4 Concept diagram of common mild steel damper types

The maximum elastic displacement of the coupling beam in a damper-added structure system is the sum of the maximum elastic displacement of the RC coupling beam and of the damper. The Airy plane stress and vertical displacement for every point in a cantilever beam under pure bending is

$$\tilde{\Delta}(x,y)=\frac{\nu Vxy^{2}}{2EI}+\frac{Vx^{3}}{6EI}-\frac{VxL^{2}}{2EI}+\frac{VL^{3}}{3EI} \tag{5}$$

Where ν is poisson ratio. And the maximal elastic displacement of the RC coupling beam is

$$\Delta_{c}(a,0)=\left(\frac{Va^{3}}{6E_{b}I_{b}}-\frac{VaL^{2}}{2E_{b}I_{b}}+\frac{VL^{3}}{3E_{b}I_{b}}\right)\cdot\left(1+\frac{3}{\lambda^{2}}\right) \tag{6}$$

Two common dampers are used in stiffness-tandem energy dissipation coupling beams, bending and shear mild steel dampers, as shown in Fig. 4. In the design process, should be comprehensive consideration of the coupling beam stiffness requirements, damper size limit, engineering cost and other factors to choose a different type of damper.

The elastic maximum displacements for these mild steel dampers are

$$\Delta_{d}=\begin{cases}\dfrac{Va^{3}}{3E_{d}I_{d}} & bending\\[2ex] \dfrac{Va^{3}}{3E_{d}I_{d}}\cdot\dfrac{3h_{d}^{2}}{4a^{2}} & shear\end{cases} \tag{7}$$

Where h_d is the cross-section height of mild steel dampers, E_dI_d is the bending stiffness of mild steel dampers. The elastic maximum displacements in the energy dissipation structure are

$$\Delta_{re}=\begin{cases}\left(\dfrac{Va^{3}}{6E_{b}I_{b}}-\dfrac{VaL^{2}}{2E_{b}I_{b}}+\dfrac{VL^{3}}{3E_{b}I_{b}}\right)\cdot\left(1+\dfrac{3}{\lambda^{2}}\right)+\dfrac{Va^{3}}{3E_{d}I_{d}} & bending\\[2ex] \left(\dfrac{Va^{3}}{6E_{b}I_{b}}-\dfrac{VaL^{2}}{2E_{b}I_{b}}+\dfrac{VL^{3}}{3E_{b}I_{b}}\right)\cdot\left(1+\dfrac{3}{\lambda^{2}}\right)+\dfrac{Va^{3}}{3E_{d}I_{d}}\cdot\dfrac{3h_{d}^{2}}{4a^{2}} & shear\end{cases} \tag{8}$$

Therefore, the displacement amplification coefficient in the energy dissipation structure is

$$R_{dis}=\begin{cases}1-\dfrac{3a}{2L}+\dfrac{a^{3}}{2L^{3}}+\dfrac{E_{b}I_{b}a^{3}\lambda^{2}}{E_{d}I_{d}L^{3}\left(\lambda^{2}+3\right)} & bending\\[2ex] 1-\dfrac{3a}{2L}+\dfrac{a^{3}}{2L^{3}}+\dfrac{3E_{b}I_{b}a\lambda^{2}h_{d}^{2}}{4E_{d}I_{d}L^{3}\left(\lambda^{2}+3\right)} & shear\end{cases} \tag{9}$$

Which are relevant to damper length, damper bending stiffness and beam span-depth ratio. For a given beam span-depth ratio, larger damper bending stiffness implies smaller R_{dis}, and first decreases then increases with increasing a. The main control method is to limit a rather than increase damper stiffness to reduce elastic displacement of energy dissipation coupling beams, since larger damper stiffness will have an adverse effect on the failure mode, and limit the choice of damper material.

Taking the first derivative of Eq. (9), for minimum R_{dis}

$$\frac{a}{L}=\begin{cases}\sqrt{\dfrac{E_{d}I_{d}\left(\lambda^{2}+3\right)}{E_{d}I_{d}\left(\lambda^{2}+3\right)+2E_{b}I_{b}\lambda^{2}}} & bending\\[2ex] \sqrt{1-\dfrac{E_{b}I_{b}\lambda^{2}h_{d}^{2}}{2E_{d}I_{d}L^{2}\left(\lambda^{2}+3\right)}} & shear\end{cases} \tag{10}$$

The right side of Eq. (10) is [0, 1), which conforms to the physical significance of a/L.

Substituting Eq. (9) into Eq. (10), the minimum displacement amplification coefficient is

$$R_{dis,\min}=\begin{cases}1-\sqrt{\dfrac{E_{d}I_{d}\left(\lambda^{2}+3\right)}{E_{d}I_{d}\left(\lambda^{2}+3\right)+2E_{b}I_{b}\lambda^{2}}} & bending\\[2ex] 1-\left(1-\dfrac{E_{b}I_{b}\lambda^{2}h_{d}^{2}}{2E_{d}I_{d}L^{2}\left(\lambda^{2}+3\right)}\right)^{3/2} & shear\end{cases} \tag{11}$$

And the damper length can be obtained from Eq. (10) for the $R_{dis,\min}$ condition.

3.2 Controlling the failure mode

For the energy consumption structure shown in Fig. 2, the ideal failure mode under strong ground motion action should be the dampers yielding before the RC coupling beam and the RC coupling beam yielding before damaging the wall.

3.2.1 Ensuring the damper yields before the reinforce concrete

The stiffness ratio between the damper and RC coupling beams controls the failure mode of RC-MSDS-TED coupling beams. This article studies the optimal yield strength ratio and yield displacement ratio between dampers and RC coupling beams to control the structure failure mode, with

$$\Gamma = \frac{F_{dy}}{F_{by}} \quad \text{and} \quad \Phi = \frac{\Delta_{dy}}{\Delta_{by}} \tag{12}$$

Where Γ is the yield strength ratio, Φ is the yield displacement ratio, F_{dy} is the damper yield force, F_{by} is the mid-span yield force of the coupling beam, Δ_{dy} is the yield displacement of the damper, and Δ_{by} is the mid-span yield displacement of the coupling beam.

To meet the shear and bending capacity demands of the coupling beam, the larger of the standard value of for shear or bending capacity should be chosen, where shear and bending capacity in the coupling beam are, respectively

$$F_{by}^{V} = 0.7 f_{tk} b h_{b0} + f_{yv} \frac{A_{sv}}{s} h_{b0} \quad \text{and} \quad F_{by}^{M} = \left(H_0 - a_s'\right) f_y A_s \tag{13}$$

The physical significance of parameters in Eq. (13) are discussed elsewhere (GB 50011-2010 2010). In accordance with the principle of strong shear and weak bending, generally $F_{by}^{M} < F_{by}^{V}$ in the design process, and the beam bending force is

$$F_{by} = F_{by}^{M} = \frac{\left(h_b - a_s'\right) f_y A_s}{L} \tag{14}$$

From the fit for yield displacement angle based on 62 specimens of coupling beam tests (Fujiang 2006), steel concrete beam yield displacement is

$$\Delta_{by} = 0.788 \frac{f_y L}{E_d}\left(\lambda + \frac{5.37}{\lambda}\right) \tag{15}$$

The damper yield force and yield displacement can be divided into two categories, depending on different damper working modes

$$\begin{cases} F_{dy} = \dfrac{n f_y b t^2}{6a},\ \Delta_{dy} = \dfrac{2 f_y a^2}{3 E_d t} & \textit{bending} \\ F_{dy} = \dfrac{f_y t h_d^2}{6a},\ \Delta_{dy} = \dfrac{f_y h_d}{2 E_d} & \textit{shear} \end{cases} \tag{16}$$

Therefore, yield ratio and yield displacement ratio for available energy dissipation in the structure are

$$\begin{cases} \Gamma = \dfrac{n b t^2 L}{6a\left(h_b - a_s'\right) A_s},\ \Phi = \dfrac{0.85\lambda a^2}{t L\left(\lambda^2 + 5.37\right)} & \textit{bending} \\ \Gamma = \dfrac{t h_d^2 L}{6a\left(h_b - a_s'\right) A_s},\ \Phi = \dfrac{0.63\lambda h_d}{L\left(\lambda^2 + 5.37\right)} & \textit{shear} \end{cases} \tag{17}$$

And in the design process, Γ and Φ should be always less than 1.

3.2.2 Ensuring the coupling beams yield before wall damage

The design principle that the RC coupling beams yield before the wall is the important basis to ensure that the coupling beam becomes the first seismic defense for the whole structure.

The following example derives design principles for beam yield before wall damage for two-limb shear walls. Fig. 5 shows the deformation and internal forces for a two-limb shear wall under lateral load, where M_1 and M_2 are the base resistive overturning moment of each wall limb under bending deformation conditions; $\tau(x)$ is the mid-span shear force of each coupling beam; T is the equivalent axial force of the wall limb, which equals the sum of all the coupling beam mid-span shear forces; D is the distance between the two axes of the wall limbs, and H is the total height of structure.

Neglecting gravity, the total bending moment at the bottom of the wall is

$$M_{total} = M_1 + M_2 + T \cdot D \tag{18}$$

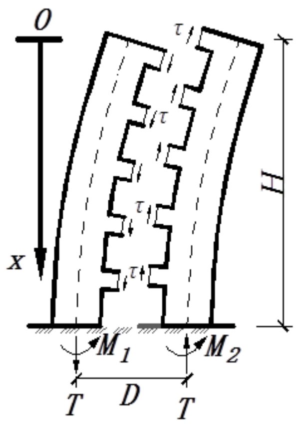


Fig. 5 Internal force for two-limb shear wall under lateral load

Use the coupling ratio to measure the internal force on the coupling beam and wall limb within the system

$$C = \frac{T \cdot D}{M_1 + M_2 + T \cdot D} \tag{19}$$

The range of the coupling ratio directly reflects the degree of restraint of the coupling beam to the wall limb. Too large or too small coupling ratio will have a negative impact on the structure. The reasonable range for the coupling ratio should be determined according to the ductility coefficient of the whole structure: coupling beam and wall limb.

For the two-limb shear wall shown in Fig. 1(a), the curvature ductility coefficient is

$$\mu_\varphi = \frac{\varphi_{\max}}{\varphi_y} \tag{20}$$

Where $\varphi_{\max}$ is the maximum bending curvature, and φ_y is the yield curvature of the two-limb shear-wall system.

Fig. 6 shows the relationship between the curvature ductility factors of the coupling beam, the wall limb and the two-limb shear wall considering the coupling effect between the coupling beam and wall limbs.

Fig. 6 is obtained based on the mechanical relationship between coupling beam, wall limb, and two-limb shear wall. The coupling beam yield curvature, $\varphi_{y,b}$, must be smaller than the wall yield curvature, $\varphi_{y,w}$, to ensure that the coupling beam yields before wall damage. The coupling beam curvature ductility coefficient, $\mu_{\varphi,b}$, should not be less than the wall limb curvature ductility coefficient, $\mu_{\varphi,w}$ when the wall limb starts to yield to ensuring the coupling beam achieves better energy dissipation. To ensure the coupling beam and wall limb reach their limit use states simultaneously, the ultimate ductility coefficient of the coupling beam should satisfy

$$\mu_{\varphi,b} = 2\mu_{\varphi,w} \tag{21}$$

From the same displacement principle, R for the long period structure can be assumed to be equal to the corresponding ductility coefficient, i.e

$$R = \frac{F_{e,\max}}{F_y} = \mu \tag{22}$$

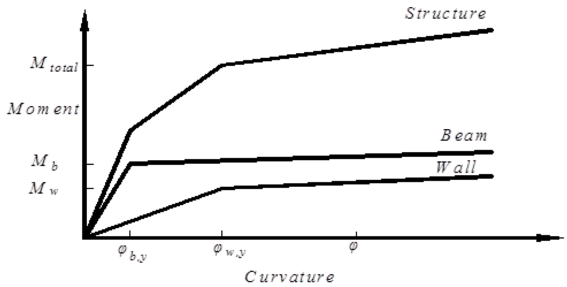


Fig. 6 Curvature ductility coefficient of the coupling beam, wall limb, and two-limb shear wall

Where $F_{e,\max}$ is the product of the maximum displacement of the structure and the elastic stiffness, and F_y is the yield force of the structure.

Thus, from Eqs. (18) and (21), the curvature ductility coefficient of two-limb shear wall can be expressed as

$$\begin{aligned}\mu_{\varphi,total} &= \frac{(M_1 + M_2)\cdot \mu_{\varphi,w} + T\cdot D \cdot \mu_{\varphi,b}}{M_1 + M_2 + T\cdot D} \\ &= \mu_{\varphi,w} + \frac{T\cdot D}{M_1 + M_2 + T\cdot D}\cdot\left(\mu_{\varphi,b} - \mu_{\varphi,w}\right) = \mu_{\varphi,w} + C\cdot\left(\mu_{\varphi,b} - \mu_{\varphi,w}\right)\end{aligned} \tag{23}$$

Fig. 6 shows that the overall curvature ductility coefficient of the two-limb shear wall structure should not exceed the curvature ductility coefficient of the coupling beam, and the overall curvature ductility coefficient of the two-limb shear wall structure should not be less than the curvature ductility coefficient of the shear wall limb. To ensure the two-limb shear wall structure has good hysteretic energy dissipation capacity, the general curvature ductility coefficient should satisfy

$$\mu_{\varphi,w} + 1 \le \mu_{\varphi,total} \le \mu_{\varphi,b} - 1 \tag{24}$$

Substituting Eqs. (21) and (24) into Eq.(23)

$$\frac{1}{\mu_{\varphi,w}} \le C \le 1 - \frac{1}{\mu_{\varphi,w}} \tag{25}$$

In general, the curvature of the wall limb ductility coefficient can be taken as 3, so Eq. (25) becomes

$$\frac{1}{3} \le C \le \frac{2}{3} \tag{26}$$

Thus, the forces between the components in the two-limb shear wall construction system are well coupled when the overturning moment caused by the shear force of the coupling beam is between 1/3 and 2/3 of the overturning moment of the total foundation.

3.3 Controlling the use limit state

When the structure or components achieve the maximum load, the energy dissipation structure should not have a deformation or local collapse unsuitable for continued load, or there will be continuous collapse of the whole structure caused by fatigue damage. Therefore, the ultimate use state of the structural system should be controlled during the design process, including controlling the limit displacement of the damper and ensuring that the damper does not suffer from fatigue failure.

3.3.1 Controlling the limit displacement of the damper

To ensure the damper has full energy dissipation and is not damaged in the limit condition, the maximum displacement angle of damper must be limited. Fig. 7 shows a deformation energy dissipation structure system under the condition of rigid coupling beam ends, where θ_w is the floor displacement angle between layers; Δ_d is the damper displacement; and L_1 and L_2 are the half lengths of the two pieces of wall limbs, respectively.

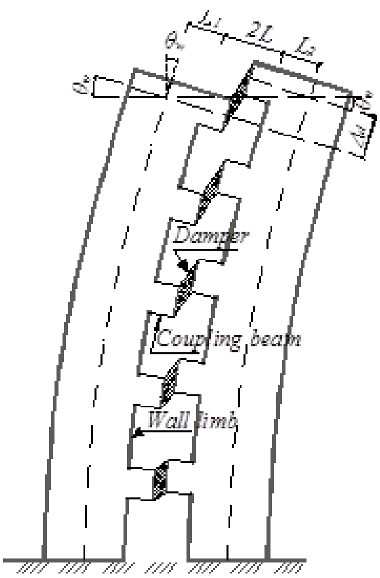


Fig. 7 Deformation of the damping structure

Thus, the displacement angle is

$$\begin{cases} \theta_d = \dfrac{\Delta_d}{2a} \\ \Delta_d = \left(2L + L_1 + L_2\right) \cdot \theta_w \end{cases} \tag{27}$$

i.e., the damper limit displacement angle is proportional to the limit layer displacement angle of the wall limbs, total coupling beam length, and wall limb length; and inversely proportional to the damper length. The limit displacement angle of elastic-plastic drift angle is 1/120 for RC shear wall structure in the Chinese seismic code, so the limit displacement angle of damper layer should be

$$\theta_{ud} \le \frac{\left(2L + L_1 + L_2\right)}{240a} \tag{28}$$

3.3.2 Avoiding dampers suffering from fatigue failure

Strength, stiffness, and fatigue life are three basic metal damper characteristics influencing normal function. Fatigue refers to material suffering performance change under alternating load, e.g. visible cracking or complete fracture. Alternating loads causing material fatigue damage are generally less than the ultimate bearing capacity under static loads, and no obvious macroscopic plastic deformation is caused before fatigue failure (Stephens *et al*. 2001). Therefore, the damage is a type of low stress brittle failure. Since fatigue failure significantly harms components or normal use function of the structure, strict rules must be followed to design material with suitable fatigue life.

Steel Q235 is commonly used for mild steel dampers, and its estimated fatigue life is

$$\frac{\varepsilon_{in}}{2} \le 0.103\left(2N_f\right)^{-0.4112} \tag{29}$$

Where ε_{in} is the inelastic strain amplitude of mild steel, and N_f is the number of cycles (Zhang *et al*. 2016). Supposing the ductility factor of mild steel damper is 5, ε_{in} can be calculated through correlation theory of material mechanics. Thus, for the two common mild steel dampers

$$\varepsilon_{in} = \begin{cases} \dfrac{4t\Delta_{d,y}}{a^2} & bending \\ \dfrac{\Delta_{d,y}}{2\sqrt{3}a} & shear \end{cases} \tag{30}$$

The current seismic design code of China requires $N_f \ge 30$ (GB 50011-2010, 2010). Therefore, combining Eqs. (27), (29) and (30), the minimum mild steel damper fatigue life is

$$\begin{cases} \dfrac{a^2}{t\left(2L + L_1 + L_2\right)} \ge 0.655 & bending \\ \dfrac{a}{\left(2L + L_1 + L_2\right)} \ge 0.047 & shear \end{cases} \tag{31}$$

Therefore, when the designed damper parameters conform with Eqs. (28) and (31), the RC-MSDS-TED coupling beam can meet the demands of the limit statement.

4. Conclusions

This paper studied the design principles and methods for metal dampers in RC-MSDS-TED coupling beams based on current research and known RC-MSDS-TED coupling beam problems. The outcomes can be summarized as follows:

- Current research status in China and abroad was summarized for RC-MSDS-TED coupling beams and current research shortcomings discussed.
- Three design principles were proposed for the metal damper in RC-MSDS-TED coupling beams based on required working performance and the role of first line of seismic defense, i.e., the coupling beam should have sufficient initial stiffness, control overall yielding and failure modes of the structure, and control the ultimate use state of the structure.
- Corresponding methods and equations were derived to realize the design principles, based on mechanical theory and structural material properties.
- Sufficient initial stiffness of RC-MSDS-TED coupling beam can be effectively achieved by controlling the length and bending stiffness of the metal damper. Thus, the length of dampers should meet the mathematic relationship of Eq. (10).
- Yielding and failure modes of the whole structure can be controlled through the yield strength ratio coefficient, yield displacement ratio coefficient, and coupling ratio, ensuring that the damper yields and fails before the coupling beam, as well as the coupling beam yielding and failing before the wall limb. Thus, the height, thickness, or length of dampers should meet the mathematic relationship

of Eq. (17) as well as the coupling ratio should fall in a certain range according to Eq. (26).

- To control the structure ultimate use state, the ultimate displacement and fatigue damage limit state of the damper can be controlled to realize the design purpose of the RC members within the RC-MSDS-TED coupling beam without serious damage to the structure. Thus, the limit displacement angle of damper should satisfy with Eq. (28) and the thickness or length of damper should meet the relationship of Eq. (31).

The relevant research results in this paper will provide theoretical support and design method guidance for popularization and application of energy dissipation coupling beam technology. However, the relationships established in this paper are derived from mechanical principles under ideal conditions, some of which need to be verified by structural tests or engineering experiments.

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