Abstract:

Application of energy dissipation devices is reasonable and cost effective to maintain main structural members in elastic state for high-rise buildings. This paper discusses required energy dissipation performance for the longperiod ground motion on M7 class earthquake and the ability of JFE hysteretic energy dissipation devices.

1. Introduction

Seismologists have recently warned of the strong likelihood that Japan will suffer an M7-class large earthquake at some point in the next three decades. If this happens, it will be particularly important to maintain the building functions of high-rise buildings after the quake[1].

JFE Steel has reached the commercial stage in the development of extra-mild steels such as an ultralow-yield-point steel (JFE-LY100) and low-yield-point steel (JFE-LY225) for hysteretic dampers, as well as three types of vibration dampers: a buckling-restraint brace type, a wall-panel type, and a stud-panel type[2]. We have also developed hysteretic and visco-elastic hybrid damper, though not yet to the point of commercialization. This paper describes important points to keep in mind in the structural design of vibration damping structures applied to recent high-rise buildings, and outlines the structural performance of the vibration dampers developed at JFE Steel. We also evaluate the performance of vibration dampers installed in high-rise buildings against long-period earthquake motions[3], and give examples of the application of JFE vibration dampers to high-rise buildings.

2. Vibration Dampers and Structural Design of High-Rise Buildings

2.1 Recent Trend in Structural Design of High-Rise Buildings

The structural design of a high-rise building reduces the plasticization and input energy during an earthquake by assigning a relatively large elastic limit to the main frame and lengthening the natural period at a safety limit, respectively, by means of use of relatively smaller section. Through these steps, we can perform examinations in pursuit of both economical rationality and seismic safety[4]. To meet these conditions, architects tend to rely on high-tensile steel materials. This can be point steel are used in 70% of energy dissipation members in dampers. LY225, a grade with relatively small strain hardening and strain rate dependence, accounts for about 90% of the steel used for dampers.

Among hysteretic dampers, the buckling-restraint brace type is the most frequently used. The wall-panel type is often constrained by building plans. Though the yield strength of the wall-panel type can be easily increased, the wall-panel structure cannot easily provide openings. The stud-panel type, on the other hand, provide openings readily. Yet as to be described later, stiffness decreases due to the effect of the bending deformation of the members supporting the damper and the beam members attached. In spite of this, the last three years have seen the increasing adoption of the stud-panel type in residential RC high-rise buildings, structures that have relatively rigid beam compared with steel structures and must be designed with passages and other types of openings. The buckling-restraint brace type seems to be studied as a hysteretic damper with balanced properties from these standpoints.

2.2 Design Method for an Effective-Moment-Resistant Frame with a Hysteretic Damper

Figure 1 shows the restoring characteristics of a moment-resistant frame (MRF) with a hysteretic damper. An MRF with a hysteretic damper is divided into a main frame consisting of columns and beams, and a damper portion consisting of a damper with connecting and supporting members. The shearing springs replacing the main frame and the damper portion are presumed to have the restoring characteristics of a complete elasto-plastic type. The ordinate of the restoring characteristics of an MRF with a hysteretic damper shown in **Fig. 1** represents the story shear force Q, and the abscissa represents the inter-story displacement δ. β is an index of yield shear force of the damper and expresses the contributional ratio of the damper portion to the maximum story shear force Q_u of the whole system. ψ, or the "trigger level coefficient," is an index of the story shear force of the whole system when the damper portion starts to dissipate energy. The ratio of the elastic stiffness K_D of the damper portion to the elastic stiffness K_F of the main frame is referred to as the "stiffness ratio k." The stiffness ratio k expresses the contributional ratio of the shear force of the damper portion and the frame in the elastic region. In the calculation of K_D, we need to consider a deformation component due to the axial expansion and contraction of a column adjacent to the damper portion.

The condition under which the damper portion of a hysteretic damper yields prior to the main flame, i.e., the condition under which a hysteretic damper holds, is $\delta_{Dy} < \delta_{Fy}$. Hence, the contributional ratio of the yield strength β of the damper portion must satisfy the following equation[5]:

$$\beta < {}_{\mathrm{U}}\beta = \frac{k}{1+k} \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots$$

LY225 can be considered 88 N/mm^2 and 225 N/mm^2, respectively, hence yield strength increases of about 2.8 times and 1.6 times can be expected for a damper using LY100 and a damper using LY225, respectively. In consideration of the yield strength increase of LY100, Fig. 2 also plots the values obtained by multiplying the upper limit value of the contributional ratio of damper yield strength by 1/2.8. This value takes on numerical values relatively close to $_{opt}$ in the range up to k = 2. That is, the damper will not lose the hysteresis damping effect early if the contributional ratio of the yield strength of the damper is set at a value less than $_{opt}$ according to k.

From the foregoing, we might assume that if the damper yield strength on each story is set at a value of not more than $_{opt}$, we would not need to consider a yield strength increase of the damper. With a damper steel material with relatively small strain hardening, such as LY225, the yield strength increase due to strain hardening has only a small effect even when the contributional ratio of the damper yield strength is set at a value in the vicinity of $_U$.

2.3 Elastic Stiffness

length of the elastic connecting section, respectively; A_{BRi} and L_{BRi} denote the sectional area of the brace and the sectional area of the connecting section, respectively; A_{BRi}^{eq} denotes the equivalent sectional area of the brace; $2L_D$ denotes the length of the span over which the damper is installed; A_{Bi} denotes the sectional area of the upper ßoor beam of the *i*-th story; and *E* denotes YoungÕs modulus.

As shown in Fig. 4(b), a relative rotational angle of $_i$ is generated in the ßoor beams of the *i*-th story. $_M\ _{yi}$ is expressed as follows using this $_i$

$$_M\delta_{yi} = \sum^{i-1}$$

d[redacted] a[redacted] lo[redacted] cy[redacted]

ty[redacted] Fi[redacted] hi[redacted] the[redacted] we[redacted] usi[redacted] am[redacted] we [redacted] actu[redacted] the [redacted] form[redacted] the v[redacted] 0.5 m[redacted] ally f[redacted] rad w[redacted] part. [redacted] applie[redacted] maxim[redacted] The re[redacted] tics ob[redacted] describ[redacted]

Base[redacted] progress[redacted] esis for e[redacted] Though l[redacted] been prop[redacted] study, in c[redacted] of design.F[redacted] an example[redacted] the experim[redacted] Yet loops qu[redacted] thermore, as[redacted] calculation ar[redacted] in terms of the[redacted] dissipation of th[redacted] 90%, and the va[redacted] angle increases. [redacted]

[redacted]ure 9 shows the relation of the number of cycles [redacted] total loading amplitude of each steel grade in the [redacted]s of the fatigue test for the shear panel. Inciden-[redacted]he number of cycles N adopted is the number of [redacted] obtained when the yield strength decreased to [redacted]f the maximum yield strength. Both the elastic [redacted] $_e$ and plastic strain $_p$ can be approximated by [redacted]ght line, and the Manson-Coffin rule holds. The [redacted]sults for LY100 were obtained from the assembled [redacted]ence the plastic strain tends to rise to somewhat [redacted]vels at low amplitudes as a result of the difference [redacted]traint conditions. On the whole, however, LY225 [redacted]ong fatigue life, exhibiting a tendency about the [redacted]s that observed in the material test results. With [redacted]e application with a loading amplitude of not [redacted]an about 0.01 rad, the fracture mode provides [redacted]acks, hence we ultimately nd little difference [redacted] the steel grades.

[redacted]atigue life curve is expressed by the following [redacted] for each steel grade:

[redacted]

[redacted] to

[redacted] life

[redacted] $= 0.112\,8$ [redacted]

damper effective in seismic response[14]. The hysteretic panel damper is composed of two studs and a horizontal member (both: H-450 × 200 × 12 × 19, SN490B9), with part of the web formed from a low-yield-point steel (t = 6 mm, $_y$ = 225 N/mm^2). The visco-elastic damper is formed by stacking high-damping rubber (t = 5 mm) made by Yokohama Rubber Company, Ltd. in two layers. We call this hybrid damper a "series-parallel" type for two reasons: rst, the damper is made up of two types of dampers; second, the visco-elastic damper is connected in series to a low-yield-point panel via a horizontal member and connected in parallel to the studs.

We tested this hybrid damper by subjecting it to dynamic loading at 0.3 and 1 Hz as shown in Photo 2. The amplitude used in the experiment is divided into small amplitudes (assumed for wind response) and large amplitudes (assumed for seismic response), with a story drift angle R of 1/500 (= 6 mm) serving as the boundary.

5.2 Experimental and Discussion

(a) Figure 24 shows the restoring characteristics of the low-yield-steel panel of the hysteretic panel damper. The maximum displacement R_{pmax} of the panel is 1/16.9 rad and the yield strength decreases due to buckling. All parts of the studs and horizontal members remain within the elastic range even after the panel buckles, except for the parts in the vicinity of the damping constant at small amplitudes of 2 to 3%.

(b) Figure 25 shows the damping ratio and constant of the visco-elastic damper. The ratio of the deformation of the high-damping rubber to the damper displacement (relative displacement between the horizontal members and the lower beam) is 75 to 90%. Though the stiffness of the high-damping rubber is almost the same as the stiffness obtained with the evaluation equation in reference[15], we use a value corrected for each cycle in the evaluation of the performance of the hybrid damper, to adjust for the slight cycle dependence. The damping constant is approximately 0.3.

(c) Figure 26 shows examples of hysteresis loops of the hybrid damper at small amplitudes. The deformation of the high-damping rubber is approximately 60% of the story drift and the contributional ratio of yield strength is approximately 25%. The damping constant