COLLISION TEST BETWEEN STEEL BARS WITH SHOCK ABSORBING RUBBER FOR BRIDGE RESTRAINER SYSTEM USING FRICTIONLESS IMPACT TESTING APPARATUS

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ABSTRACT

In the Japanese Specifications for Highway Bridges, shock absorbing rubbers should be required to reduce the impact load with the collision between a superstructure and a device which prevents a superstructure from falling off, or between two superstructures. However, the specification has no detail prescript regarding the thickness of shock absorbing rubbers. Therefore, it is very important to investigate the effect of the thickness of shock absorbing rubbers on the reduction of impact load. In this study, the collision test between two steel solid bars using a new experimental apparatus is carried out in order to assess the above effect. This new apparatus can levitate a steel bar by using compressed air so that there is little friction between a steel bar and a guide rail against the horizontal movement. We name this apparatus as “frictionless impact testing apparatus”. The steel bar has 1000mm long, 200mm wide, 200mm high and about 3.0kN weight and the thickness of shock absorbing rubbers ranges from 2mm to 40mm and the collision velocity ranges from 0.2m/sec to 1.0m/sec on 7 stages. From the test results, it is confirmed that the sliding friction force is very small. In addition, the qualitative influence of the rubber thickness and collision velocity on the reduction of the maximum impact load is clarified in collision between two steel bars with shock absorbing rubber for bridge restrainer system.

INTRODUCTION

After the 1995 Hyogoken-Nanbu Earthquake, bearings have frequently been replaced by rubber bearings in order to improve earthquake resistance. When the rubber bearings are used, the inertial force of the superstructure subjected to the pier can be reduced so that the damage of the pier is lessened. However, the displacement response of the superstructure increases. Therefore, it is expected that frequency of the pounding phenomena will become large, e.g., the pounding girders and the collision between the superstructure and the abutment, etc., will increase.

When a girder collides with another girder, an abutment and a device which prevents a girder from falling off, the girder is subjected to the impulsive force. So, there is a possibility that the girder ends will be damaged.
In the worst case, an emergency car cannot traverse the bridge shortly after a strong earthquake occurs because of the damage of the girder ends. Therefore, in order to reduce the impact force during a collision, the Japanese Specifications of Highway Bridges requires that shock absorbers, such as those made of rubber, be installed at the girder ends in addition to devices which prevent girders from falling off. However, the specification has no detail prescript regarding the thickness of shock absorbing rubbers because it has not clarified how much impact force is produced during a collision. Therefore, it is very important to investigate the influence of the thickness of shock absorbing rubbers on the impact load.

Several studies focusing on the collision problem have been carried out (Kubota et al., 1997, Sonoda et al., 2001, Murata et al., 2001). In these papers, a mass collides with a concrete wall which is fitted with several kinds of shock absorbers, such as a natural rubber, a piece of synthetic resin, a sandbag etc. From the results of these researches, it was found that the shock absorber has a quantitative effect on the reduction of the impact force. However, to focus on the pounding girders, the method of these tests cannot replicate the circumstances of the pounding girders. Therefore, we develop the new test apparatus which can levitate two steel bars by using compressed air. By using this test apparatus, two objects move freely into a horizontal direction without kinetic friction.

In this paper, the collision test between steel bars is carried out as the first step toward developing the design method of the shock absorber. Eight kinds of the thickness of the natural rubber are prepared and seven kinds of the collision velocity are set. We summarize the maximum impact force by focusing on the difference of the thickness of the shock absorber and the difference of the collision velocity.

**OUTLINE OF THE COLLISION TEST**

**Test setup**
The collision test is carried out by using a horizontal hydraulic high-speed loading machine as shown in Photo 1. This machine has a loading capacity of 1000 (kN) and a maximum loading speed of 3.0 (m/s). The collision test was carried out as follows: (i) two steel bars are set in a line on a guide rail with a length of 3000 (mm) as shown in Figure 1 and Photo 2. (ii) Two steel bars hover above the guide rail by using the compressed air.
(iii) One steel bar rests above the guide rail and the horizontal hydraulic high-speed loading machine drives the other up to a certain velocity. (iv) The collision between girders is simulated in this way. The rectangular solid steel bar was 1000 (mm) long, 200 (mm) wide and 200 (mm) high, and its mass was 300 (kg). In this test, the specimen to which the initial velocity is applied is named the colliding specimen, and the specimen resting above the guide rail before the collision is named the collided specimen, respectively. When the specimen is moving, the sliding friction force slows the movement of the steel bars. In this test, however, the sliding friction force is reduced by using the compressed air. Therefore, the energy loss caused by the sliding friction force is suppressed during the collision.

Measuring system
As for a collision problem involving two bodies, there are three characteristic measures to be evaluated: the impact force, the law of conservation of momentum and the kinetic energy loss. In this study, in order to evaluate these measures, the impact force during the collision and the velocity before and after the collision are measured. In order to determine the velocity of the steel bars, the traveling distance of the colliding and collided specimens and the relative displacement between two specimens are measured by a laser displacement sensor. The method of least squares is applied in order to obtain the velocity of the specimen from the time history of movement. To be more precise, the velocity of the specimen is found by approximating the time-displacement relationship with the linear expression with respect to time. The impact force working on the collision surface is measured by a load cell which is installed on the edge of the steel bar as shown in Photo 3. Two kinds of the load cell are prepared in this test. The load rating of two load cells is 500 (kN) and 3000 (kN), respectively. In the case that the shock absorber is installed, the one whose load rating is 500 (kN) is used. On the other hand, in the case that the shock absorber is not installed, the other one is used. The case where the shock absorber is installed, the sampling time of the measurement is set at 5.0×10^{-5} (sec). On the other hand, the case where the shock absorber isn’t installed, that is set at 1.0×10^{-5} (sec).

Shape of shock absorbers
In this test, natural rubber is prepared as shock absorbers. The natural rubber has a degree of hardness of 50 (JIS K 6301). The shape of the natural rubber is a cuboid. The cross section of the rubber has 40 (mm) long, 40 (mm) wide. The thickness is 2, 3.5, 6, 8, 10, 20 and 40 (mm) respectively. So, the ratio of the pressed area to free surface area ranges from 0.2 to 4.0. We call this ratio as the shape factor. As mentioned before, there is no rule to determine the thickness of the shock absorbers. The bridge designer generally uses the shock absorbers whose shape factor is from 0.3 to 1.0. Therefore, the prepared natural rubber covers the range of the shape factor of the natural rubber which is installed in the real bridge.

Setting velocity
According to the similarity law, the velocity of the scaled model is equivalent to that of the actual phenomenon because this test is not influenced by gravity (Emori et al., 2000). K. Izuno and S. Takeno performed numerical
analysis of an elevated bridge (Izuno and Takeno, 1999) and made clear that the response velocity of the superstructure is from about 0.5 (m/s) to 3.0 (m/s) during severe ground motion such as the 1995 Hyogoken-Nanbu Earthquake. Therefore, the initial velocity of the colliding specimen is set from 0.2 (m/s) to 1.0 (m/s) on 7 stages.

Material properties of natural rubber
Before the collision test is carried out, the static compression test on the shock absorbers is carried out by using the 50kN compression test machine. The compression load is applied until the shock absorber is compressed to up to 60% of the original height in the case that the thickness of the natural rubber is more than 6 (mm). In the case that the thickness of the natural rubber is 2 (mm) and 3.5 (mm), the compression load is applied until the shock absorber is compressed to up to 40% of the original height. The load-deformation curves of the shock absorbers are shown in Figure 2. In Figure 2, the thinner the thickness of the natural rubber is, the smaller the stiffness of the natural rubber is. In the case that the thickness is 2.0, 3.5 (mm), the stiffness becomes large suddenly when the strain goes over 0.3. In the other cases, the stiffness becomes large suddenly when the strain exceeds 0.4.

TEST RESULTS AND DISCUSSION

Effect of sliding friction force
Before the discussion of the test results, it is important to examine whether the sliding friction force between the specimen and the guide rail has an effect or not on the velocity of the specimen. At first, one steel bar is removed from the guide rail. So, only one steel bar remains on the guide rail. We give the steel bar a certain velocity and measure the velocity of the bar at two points. The coefficient of slide friction is obtained from the velocity of the bar at two points as follows.

$$\mu = \frac{V_2^2 - V_1^2}{2dg}$$

in which $\mu$, $V_1$, $V_2$, d and g are the coefficient of sliding friction, the velocity of the bar at two points, the
distance between two points and the acceleration of gravity, respectively. From Equation (1), the coefficient of sliding friction is obtained from 0.0010 to 0.0063 as shown Figure 3. So, the sliding friction is as small as we can neglect. To sum up, the energy dissipation due to the sliding force is neglected in this test setup.

Measured velocity just before the collision
The tests are performed more than twice for all the cases. For example, in the case of the setting velocity of 0.7 (m/s), the test is carried out 10 times. The collision velocity measured by the laser displacement sensor has a little variation, e.g., from about 1.191 (m/s) to 1.256 (m/s) as shown in Figure 4. From this figure, it can be seen that the measured collision velocity of the colliding specimen is 1.7 times as the setting velocity and we can regard the measured velocity as the constant value under the same setting velocity.

Figure 4 Relation between setting velocity and measured velocity

Figure 5 Relation between maximum impact force and shape ratio

Relationship between the thickness of the rubber and the maximum impact force
Figure 5 shows the relationship between the shape ratio and the maximum impact force at the measured velocities of 1.21 (m/s) and 1.65 (m/s). The setting velocities are 0.7 (m/s) and 1.0 (m/s), respectively. From Figure 5, the relationship curves delineate rectangular hyperbola. When the shape factor is smaller than 0.3, the maximum impact force becomes large sharply. In other words, if the shape factor is larger than 0.3, the advantage of the reduction of the maximum impact force is obtained.

Relationship between the measured collision velocity and the maximum impact force
Figure 6 shows the relationship between the measured velocity just before the collision and the maximum compression strain and Figure 7 shows the relationship between the measured velocity just before the collision and the maximum impact force. In Figure 6, in the case of the thickness of the shock absorber of 3.5 (mm), the maximum strain becomes over 1.0 at the high-speed area. This is because the relative displacement between two steels isn’t measured properly since the thickness of the shock absorber is very thin. From Figure 6, it can be seen that the measured collision velocity and the maximum strain are proportionality relation. Furthermore, when the measured collision velocity becomes over 1.0 (m/s), the maximum strain becomes over 0.6. Considering the load-deformation curves of the shock absorbers as shown in Figure 2 before, it can be found that the natural rubber becomes hardened completely. From Figure 7, the maximum impact force - the collision velocity curve can be approximated by using two linear lines. The intersection lies in near the collision velocity of 1.0 (m/s). That is to say, when the shock absorber becomes hardened, the rate of increase of the maximum impact force becomes large. So, in the design of the bridge, the engineer should be pay attention to the collision velocity of the girder.
(a) thickness of 3.5 mm, shape ratio of 0.35
(b) thickness of 6 mm, shape ratio of 0.6
(c) thickness of 8 mm, shape ratio of 0.8
(d) thickness of 10 mm, shape ratio of 1.0

Figure 6 Relation between the collision velocity and the maximum compressive strain

(a) thickness of 3.5 mm, shape ratio of 0.35
(b) thickness of 6 mm, shape ratio of 0.6
(c) thickness of 8 mm, shape ratio of 0.8
(d) thickness of 10 mm, shape ratio of 1.0

Figure 7 Relation between the maximum impact load and the collision velocity
CONCLUDING REMARKS

In this paper, we develop the new test apparatus which can levitate a steel bar by using compressed air so that there is little friction between a steel bar and a guide rail against the horizontal movement. The collision test between two steel bars is carried out by using this new test equipment in order to investigate the effect of the thickness of the shock absorber on the impact force. The conclusions and future research needs are described as follows:

(1) By using the newly developed test apparatus, the generation of the sliding friction force is controlled. In fact, the coefficient of dynamic friction is as small as less than 0.0035.

(2) In this test, in the thickness of 0 mm to that of 10 mm range, the maximum impact force is reduced gradually. However, the maximum impact force is almost same when the thickness of the natural rubber is more than 10 mm.

(3) The relationship between the collision velocity and the maximum deformation of the rubber can be approximated by using the linear curve. On the other hand, the relationship between the collision velocity and the maximum impact force can be resembled in the parabolic curve.

(4) The maximum impact force depends strongly on the collision velocity and the thickness of the natural rubber. So, when the size of the shock absorber is designed against the pounding girders, the collision velocity is regarded as one of the most important design variable.

This collision test is carried out as the first step toward developing the design method of the shock absorber. The data obtained from the test is not enough to establish the calculation formula of the maximum impact force under the pounding girders. Therefore, in the future, additional tests should be carried out. In particular, it is necessary to investigate the effect of the steel weight on the maximum impact force.

References


