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# BONDING BEHAVIOR IN BRIDGE STEEL-REINFORCED ELASTOMERIC ISOLATORS

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## ABSTRACT

Steel-reinforced elastomeric isolators (SREIs) have been shown to be efficient devices to protect structures against moderate and severe earthquakes by isolating them from ground motions. Bridge elastomeric isolators, however, deteriorate when undergone repetitive loading cycles due to either earthquakes or traffic loadings. One major damage type observed dominantly in these devices is delamination or de-bonding between rubber and supporting plates and steel reinforcements, if cold-bonded. This paper investigates potential damage scenarios likely to occur in cold-bonded bridge SREIs. It also looks into bonding properties of rubber and steel in tension and shear, the two important functional characteristics of elastomeric isolators. In this study, experimental tests are employed in order to observe the bonding behavior between rubber and steel. Damage states have been organized and it is observed that the adhesive properties and level of shear deformations govern bonding characteristics.

Keywords: Steel-reinforced rubber bearing, base isolation, bonding, rubber bearing damage states, shear bond, adhesive shear strength

## 1. INTRODUCTION

Designing structures resistant against unexpected loadings, such as earthquakes or heavy traffic, has been the main point of attention for bridge engineers for the past four decades (Jangid and Datta; Kelly). Base isolation has been used for this purpose since 1970s to keep structures safe during these destructive events (Hwang and Chiou). Among the various devices introduced for isolation purposes, elastomeric bearings have gained significant attention. They provide the structure with adequate vertical stiffness, needed to withstand vertical forces, while increasing its flexibility in horizontal direction. This fact causes an effective shift in structure’s natural frequency to get far enough from typical excitation ranges. Thus, it provides sufficient isolation to prevent or minimize serious damages. This phenomenon is looked-for, since it keeps important infrastructures, such as bridges, safe and functional during devastating incidents.

Based on current design codes, bridges need to be designed for a service life of more than 50 years. Elastomeric bearings, however, deteriorate due to repeated traffic loadings, earthquakes, temperature changes and severe weather, especially in regions with varying climate. As a result, they require constant monitoring and maintenance to look for potential defects and damages. Such monitoring system would be capable of giving early-enough notifications to repair the isolators, if possible, or replace them, if needed. This will not only prevent bridge components from serious damages due to bearing failure, but also will retain the facility functional throughout its service life. This study aims at characterizing the bonding between individual components of steel-reinforces elastomeric isolators (SREIs) in cold-bonded applications. The behavior of rubber, along with the adhesive, is observed in shear and tension, the two important functional characteristics of such elastomeric isolators. This research's findings can be used to identify and detect damages in SREIs and increase the certainty in estimating bridge bearings' service life.

Although extensive research has been conducted on SREIs' behavior, no distinct damage identification is developed to detect and characterize defects in them. Bonding defects tend to develop mostly in shear, the main application in which bearings are expected to function. In this study, the cold bonding between rubber and steel is investigated through experimental research, based on ASTM and AASHTO standards, described in succeeding sections.

## 2. BONDING IN STEEL-REINFORCED ELASTOMERIC ISOLATORS

SREIs are composed of three main components: a) elastomer, b) steel reinforcements and c) adhesive. This composition is then bonded to supporting steel plates which are of a higher thickness than the steel shims and used to mount the bearing between the superstructure and its foundation. Elastomer's responsibility is to provide the lateral flexibility, while steel shims are responsible to bring the vertical stiffness and load-carrying capacity to the bearing. These two components are bonded through two different procedures: 1) hot vulcanization and 2) cold bonding. Even though the former results in a more integrated bonding between the rubber and steel shims, cold bonding behavior characterization is still of interest in the applications that hot vulcanization process is not an option. Cold bonding is also used to attach the elastomer parts to supporting steel plates, even in hot-vulcanized bearings. In these cases, a common damage scenario is delamination, initiating from the bonding at supporting plates where stresses concentrate (Hedayati Dezfuli and Alam). This defect will make the bearing highly prone to propagation and can cause a widespread failure, which highlights the importance of studying bonding between these two materials.

The behavior of bonded rubber and steel in shear is addressed in four rubber and adhesive standard tests: 1) ASTM D429 (*Standard Test Methods for Rubber Property - Adhesion to Rigid Substrates - D429-14*), 2) ASTM D816 (*Standard Test Methods for Rubber Cements*), 3) ASTM D4014 (*Standard Specification for Plain and Steel-Laminated Elastomeric Bearings for Bridges*) and 4) AASHTO M251-06 (*Standard Specification for Plain and Laminated Elastomeric Bridge Bearings*). Among these four, ASTM D429 and ASTM D816 specifically look into the bonding between the two materials as one flexible and one rigid substrate. Both tests are designed to be conducted using universal tensile testing machines. The two following sections explain the procedure of each test.

### 2.1 Shear bond test

The shear bond test (ASTM D429 – Method H) characterizes the quality of bonding between rubber and steel, as a rigid substrate, in shear applications. A quadruple shear test specimen is used in this test, the illustration of which is shown in **Figure 1**. The test specimens are designed to make a symmetric double sandwich arrangement, dimensions of which are given in **Table 1**. It is important in this test to apply a uniform shear strain to the specimens, using a power-driven tensile test machine. A head separation with a rate of 0.83 ± 0.08 mm/s is required and instantaneous measurements of force and displacement are recorded and the test is continued upon failure of the specimen.

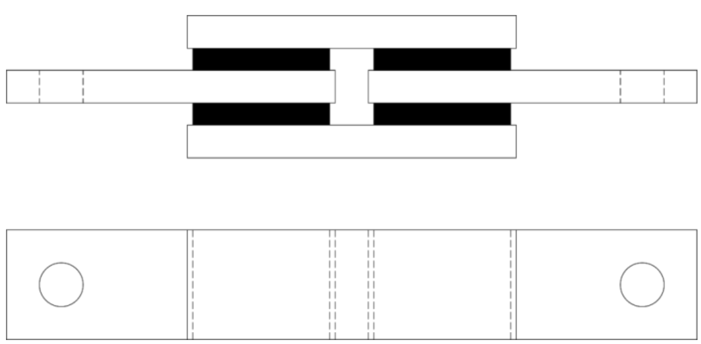

Figure 1: Schematic view of shear bond test specimens

Table 1: Shear bond test specimen dimensions

| | Rubber pieces | Steel pieces |
|---|---|---|
| Shape | Rectangular | Rectangular |
| Dimensions (Length x Width) | 25.0 x 20.0 | 60.0 x 20.0 |
| | Thickness: 4.0 ± 1 mm | Thickness: 6.0 ± 0.1 mm |

Failure in specimens is to be classified into four categories: failure in the rubber (denoted as type R), failure at the rubber-cover cement interface (RC), failure at the cover-cement prime cement interface (CP) and failure at the metal-prime cement interface (M). This failure shall be followed by a failure percentage using a visual examination of the failed area, expressing the length of de-bend in the mentioned failure category. It is also necessary in this test to report the environmental exposure conditions.

### 2.2 Adhesive shear strength

The shear bond test, previously explained, focuses on material properties of rubber in shear applications. The adhesive shear strength test, however, focuses on characterizing rubber cement's properties in the same application. For this purpose, sandwich specimens are introduced to measure the adhesion strength between a rigid and a flexible material, schematic views of which are given in **Figure 2**.

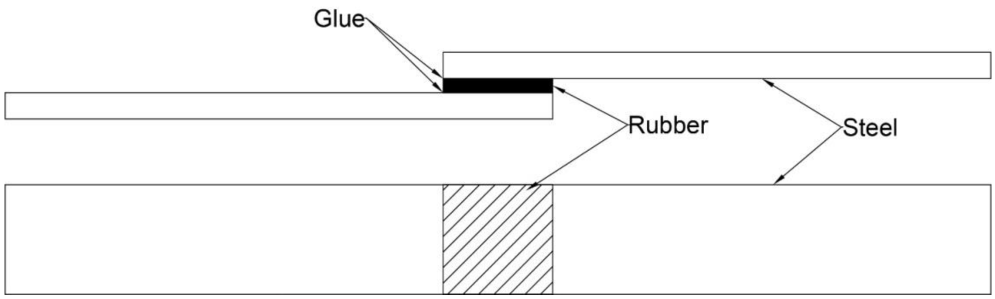


Figure 2: Schematic view of adhesive shear strength test specimens

In this test, specimens are clamped and tested in a tensile testing machine, separating the heads of the machine at a rate of 0.8 mm/s. The force-per-adhered-surface, in kilopascals, is continuously measured. Two specimens are tested and the higher strength is reported, provided that the lower value is within 10% of the higher value. If the condition is not met, additional specimens are tested until a higher value with a lower one checking within its 10% are found. If not found within 6 specimens, the average of 6 specimens is reported as the average adhesion strength in shear.

## 3. EXPERIMENTAL RESEARCH

Two series of tests are conducted in order to measure the bonding characteristics between rubber and steel, as described in Section 2 of this article. One of the factors that can highly affect the bonding properties is the type of the adhesive used. In this research, we conducted the experiments on two adhesives: 1) Strong Bond rubber cement and 2) Loctite 4851 instant adhesive. Test specimens for adhesive shear strength and shear bond properties were fabricated with regards to corresponding test standards. **Figure 3** shows fabricated specimens for the shear bond and adhesive shear strength tests.

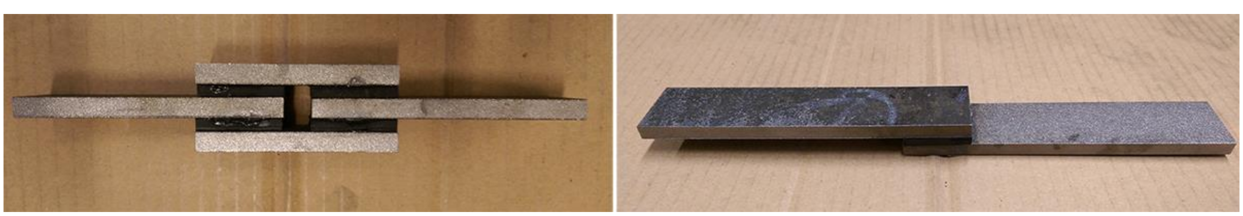

Figure 3: Fabricated specimens for shear bond test (left) and adhesive shear strength test (right)

## 4. RESULTS AND DISCUSSION

In this part, the results for previously-discussed tests will be expanded.

As previously described in this context, two sets of experiments were conducted in order to examine the behavior of rubber and its adhesion to steel in shear. The first set defines the requirements for plain and steel-laminated elastomeric bearing pads for bridges. In this test, quadruple shear specimens are fabricated and tested in a tensile testing machine to simulate pure shear conditions on rubber parts.

### 4.1 Shear bond test

In this test, quadruple shear specimens are loaded up to failure, in order to capture the performance of the bonding in shear. The quadruple specimen design helps to maintain a pure shear condition throughout the experiment. As per the standard requirement, three specimens were tested. The data was continuously recorded up to failure. **Figure 4** shows the force-displacement curves for tested specimens. A good agreement and consistency is observed among the results, making accurate enough to rely on.

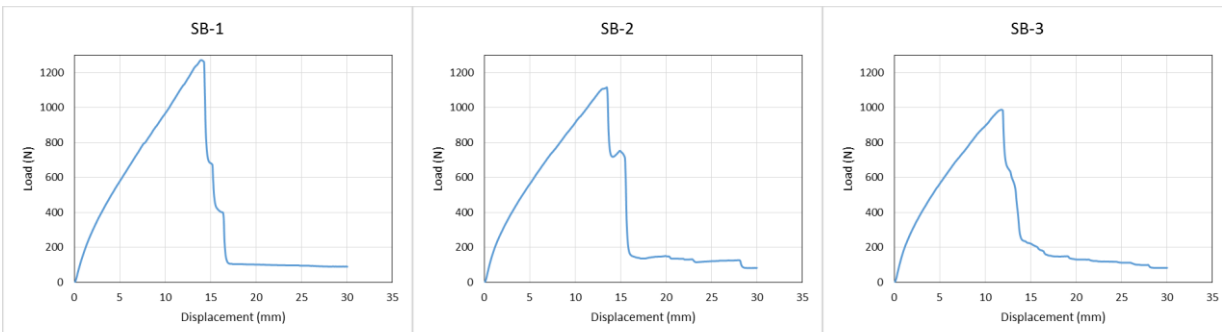

Figure 4: Force-displacement curves for shear bond test experiments

It is observed that, in all specimens, the de-bonding initiates at the edges of the rubber-to-steel bond, as shown in **Figure 5**. This de-bonding then progresses towards the entire bonded area, causing a separation between the weakest bond among the four rubber parts. This phenomenon changes the path of the load in the quadruple specimens and increases the burden on other bonds, causing a sudden collapse of the specimen. **Figure 6** below demonstrates this observation.

Figure 5: Initiation of de-bonding in shear bond tests

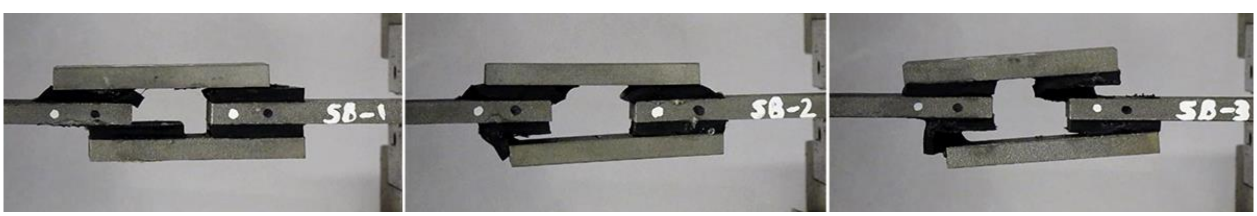

Figure 6: Damage scenarios in shear bond tests

### 4.2 Adhesive shear strength

Adhesive shear strength test specimens, as described in Section 0, are loaded in shear using a tensile testing machine. The shear strain application is continued until a complete failure in the specimens and the force-displacement data is continuously recorded. Tests are conducted in three replications, as suggested by the standard. **Figure 7** below plots the force-shear strain curves for these specimens.

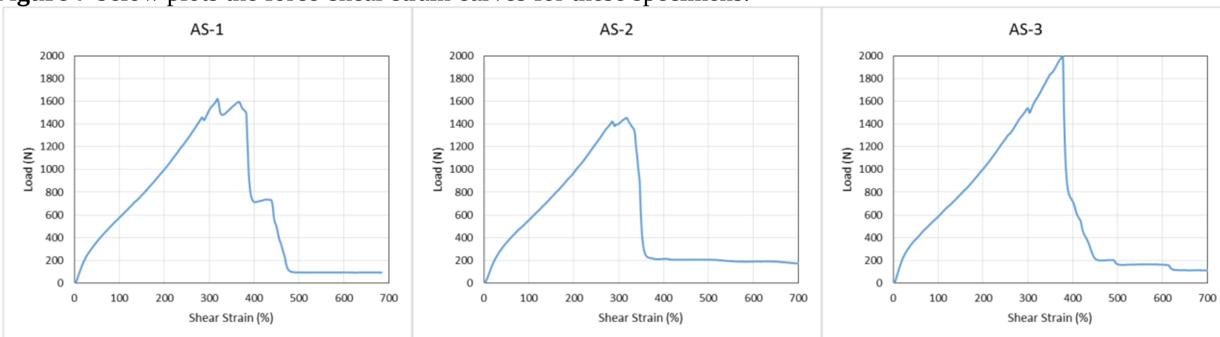


Figure 7: Force-displacement curves for adhesive shear strength experiments

In these tests, similar to shear bond tests, the separation between steel and rubber initiates from rubber edges. However, a partial rupture of rubber is later on observed, combined with glue failure. The step-wise force decay observed in **Figure 7** shows the failure stages, which includes: 1) defect initiation, 2) rubber partial rupture and 3) separation (complete failure). **Figure 8** and **Figure 9** show the preliminary stage of damage initiation and the damage state in these experiments, respectively.

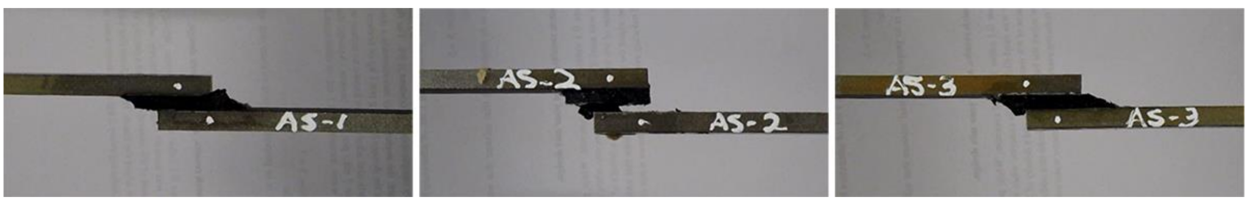


Figure 8: Initiation of de-bonding in adhesive shear strength tests

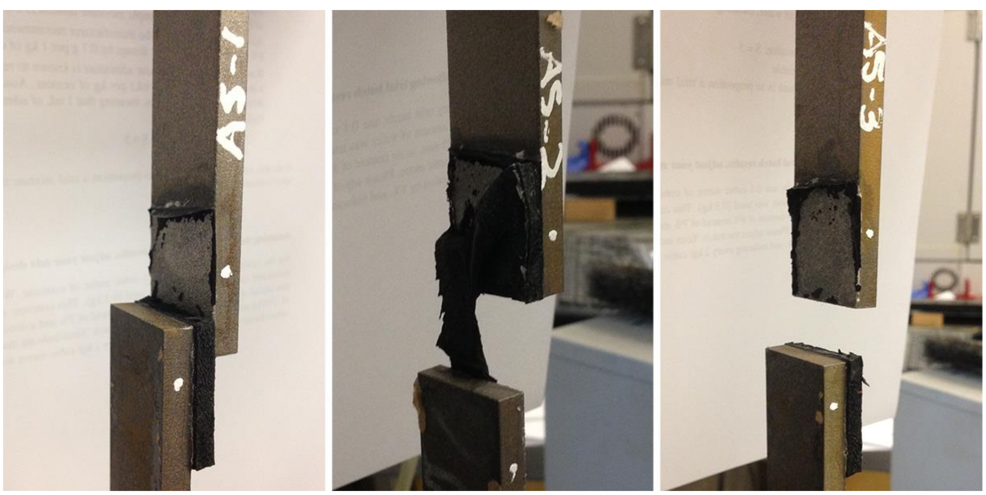


Figure 9: Damage scenarios in adhesive shear strength tests

### 4.3 Adhesive type effect

In addition to the bond tests explained above, two adhesives were compared in order to observe the effect of adhesive type. The Strong Bond adhesive was chosen, since it is designed specifically for rubber-to-steel bonding applications, known as rubber cement. The adhesive needs to be applied carefully with respect to manufacturersuggested application procedure. This process included cleaning and roughening the surfaces of both rubber and steel, applying a first coat of properly mixed adhesive-hardener mixture on both surfaces and, finally, applying a second coat of the mixture, again on both surfaces, after 1 hour. The two surfaces are thereafter ready to be put together under pressure once the coats are tacky – i.e. approximately after 20 minutes. Tests conducted on this glue showed that, despite having a good performance in whole rubber bearings, this adhesive cannot be used to get the bonding properties, as it undergoes early separation and does not provide the full behavior of the bonding. Loctite instant glue was used afterwards in order to get the full force-displacement curves for bonding tests. Although this glue is not economically efficient to be used in rubber bearing manufacturing applications, it could lead to a insightful understanding of the glue behavior in shear applications. **Figure 10** shows some of the test specimen manufacturing and testing stages, along with the typical failure type observed in experiments with rubber cement as the bonding agent.

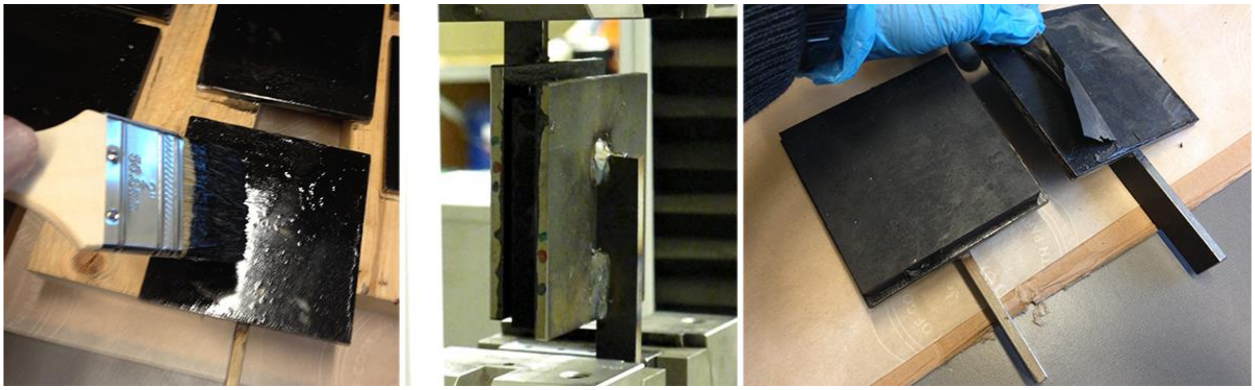

Figure 10: Test steps for rubber cement characterization

## 5. CONCLUSION AND RECOMMENDATIONS

Potential delamination scenarios likely to occur in steel-reinforced rubber bearings are investigated in this research. Two main rubber and steel adhesion standard tests are considered: 1) shear bond test and 2) adhesive shear strength, which study the effectiveness of the adhesion between rubber and steel in shear. Experimental research is employed and the following conclusions are made:

1. Bonding damages in bearings under shear can be attributed to two main reasons: 1) adhesive inadequacy and 2) rubber rupture.
2. Adhesive type directly affects the properties of bonding in shear. Furthermore, the quality of applying the adhesive also defines the quality of the formed bond. As a result, adhesive application instructions should be followed meticulously, including surface preparation and curing instructions.
3. A preferred bonding is a bonding in which rubber rupture occurs prior to adhesive failure. Hence, an adhesive with a strength higher then rubber rupture needs to be chosen for cold bond applications.
4. Even in the case of rubber rupture, adhesive plays a significant role in the bonding behavior, as it can control the damage initiation and propagation.
5. Bonding damage, once happened, will not only reduce the capacity of the damaged component, but also will decrease the load-carrying capacity of the whole bearing and expedites the failure in other parts of it.
6. Reinforcing edges help prevent the initiation of delamination.

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