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Technical Note

Failure modes in three-point bending tests of cement-steel, cement-cement and cement-sandstone bi-material beams

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Tensile strength of cement-steel and cement-rock interfaces is an important input parameter when predicting well integrity failure in petroleum industry as well as during underground CO_2 storage. Laboratory tests of interface strength (e.g. the so-called pushout test) often provide estimates of shear rather than tensile strength. In this work, three-point bending test of bi-material beams was used to study tensile failure at cement-steel, cement-cement, and cement-sandstone interfaces. The tests revealed that cement-steel interfaces were the weakest ones, while cement-cement interfaces were the second weakest. Cement-sandstone interfaces were apparently quite strong: both tested cement-sandstone beams broke inside the cement, *ca.* 2–3 cm off the interface. This surprising result, i.e. the interface being stronger than the hardened cement, was attributed to water suction from cement into the dry sandstone during setting, which was corroborated by the observed very uneven fracture surface. All bi-material beams had lower flexural strength than monolith cement beams.

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1. Introduction

Interfaces between cement and steel or rock are common in well construction in oil & gas industry. After a wellbore is drilled, a steel pipe called casing is run into the hole in order to prevent the surrounding rock from collapsing (Fig. 1). Cement slurry is then pumped into the annulus between the casing and the rock in order to keep the casing in place and to prevent formation fluids from entering the annulus and flowing along the well. In order to ensure integrity of the well, the annulus behind the casing should be completely filled with cement [1,2].

During subsequent life of the well, casing and cement can be subject to thermal and mechanical loads that may tend to separate the cement sheath from the casing pipe or the rock. This may happen, for instance, if the well is cooled down by the circulating drilling fluid or during injection of cold fluids. Cooling is likely to induce tensile radial stresses in the cement sheath [2]. If these stresses become sufficiently high, tensile failure may occur. Since interfaces between cement and other materials are often weaker that the bulk cement, tensile failure at the interface between cement and steel (or rock) is one of the standard failure scenarios in well integrity analysis [3]. Tensile strength of cement-steel and cement-rock interfaces is thus an important input parameter in well integrity models [2].

The role of interface strength in well construction has been recognized in the industry for a long time [1]. Despite the importance of tensile strength, focus has so far been on the shear strength of cement bonding. A number of methods are in use for shear strength measurements of cement interfaces with other materials. For example, Frigione et al. [4] conducted their experiments on compound cylindrical specimens obtained by cutting a cement cylinder along an oblique plane and joining the resulting two halves with an adhesive (epoxy resin). Uniaxial loading of the compound cylinder to failure provides an indication of the interface bonding strength in shear mode.

Another type of test commonly used to measure the shear strength of cement interfaces is the so-called pushout test [1,5]. In one version of this test, used by Opedal et al. [5], a rock cylinder was inserted inside a cylindrical steel shell, and the annulus between the rock and the steel was filled with cement slurry. After the slurry had hardened, the rock cylinder was pushed along its axis while the cement sheath and the steel shell were supported from beneath. The compound specimen broke along the rock-cement interface, which enabled the authors to evaluate the shear strength of the interface (pushout force divided by the interface area).

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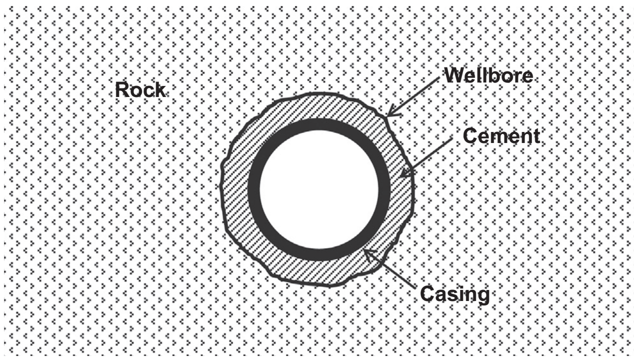

Fig. 1. Cross-section of cased and cemented well.

Tensile strength of the interface between cement and steel (or rock) can be evaluated using compound, bi-material specimens in a variety of setups. For instance, a cylindrical specimen composed of two materials, with the interface being perpendicular to the specimen's axis, could be subject to direct tension [6]. In such a test it is, however, impossible to obtain a stable crack propagation, and thus it is not possible to evaluate the *fracture energy*. Another type of test, one that is often easier to perform and that may enable evaluation of not only the tensile strength, but also the fracture energy, is the three-point bending test on a compound beam [7].

A schematic view of three-point bending test performed on a bi-material beam is shown in Fig. 2. The test can be performed either on a pre-notched beam or on a beam without notch, such as the one shown in Fig. 2. In this study, experiments were performed on beams without notch, therefore the crack propagation was unstable. Fig. 2 shows the setup with a compensated beam, i.e. the two supports are positioned in the middle of the half-beams. This eliminates the parasitic moment due to gravity that would otherwise be created in the middle of the beam.

Three-point testing of beams composed of several materials has been used to measure bonding strength of dental materials [8], cements used in knee replacement surgeries [9], and in construction industry [10].

The objective of this study was to investigate failure modes of bi-material beams in three-point bending tests, where half of the beam was made of cement. The other half was made of cement, sandstone, or steel. It should be noted that strength values of cement (and rocks) usually are quite scattered, as is typical of heterogeneous materials. It was not the goal of this study to collect sufficient statistics to quantify the strength values (which may differ significantly between different tests with the same bi-material combination), but only to demonstrate significant differences in failure modes between different combinations (which are quite consistent between the tests). Preparation of bi-material beams is described in Section 2. The experimental set-up is described in Section 3. Experimental results are presented in Section 4. Discussion and Conclusions are provided in Sections 5 and 6, respectively.

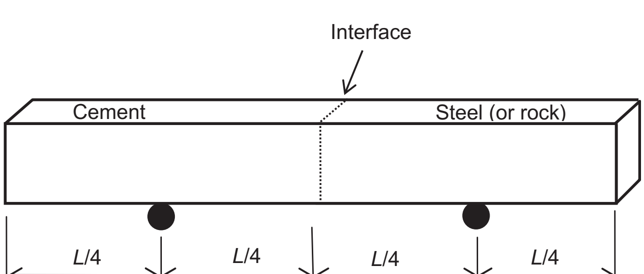

Fig. 2. Three-point bending test of a compensated bi-material beam. L is the beam length.

2. Preparation of bi-material beams

To ensure preparation of reproducible cylindrical samples, a silicone mould was first made. For the mould preparation, 10 kg of silicone MM 940 and 530 g of catalyst MM CAT B5 NT were mixed together until the mixture became homogeneous. Care was taken to prevent air entrapment in the fluid mixture. The silicone was used without degassing. The mixture was then poured into a wooden dismountable form (70 × 15 × 15 cm). A metal bar (60 × 5 × 5 cm) was hanged in the middle of the form so that the distances between the inner walls of the form and the parallel walls of the metal bar were equal to 5 cm (Fig. 3a). The silicone was allowed to cure for 48 h at ambient conditions before it was taken out of the mould, and the metal bar removed (Fig. 3b).

Five beam specimens were thereafter manufactured in the silicone mould, each having dimensions of approximately 60 × 5 × 5 cm:

- one reference specimen (monolith cement)
- two cement-cement bi-material specimens
- two cement-sandstone bi-material specimens.

Portland G cement was used in this study. Water used in the cement slurry was tap water of Trondheim municipality quality. The mixing procedure was in accordance with API specification 10A. Cement was mixed with a water/cement mass ratio of 0.44. The cement slurry was poured into the form right after mixing. The slurry was allowed to cure at ambient conditions for 24 h before the hardened specimen was removed from the silicone mould by turning the mould upside down (see e.g. Fig. 3c for the preparation of the monolith cement beam).

In the case of a monolith cement specimen (reference specimen, Fig. 3d), the entire mould was filled with the slurry. Each cement-cement bi-material beam was prepared by first making a half of the beam, with dimensions 30 × 5 × 5 cm. The metal half-beam was placed in the mould and the cement slurry was poured into the remaining empty space. After 24 h of curing, the metal half-beam was removed, and the volume was filled with freshly prepared cement slurry of the same composition as stated above. This created a compound cement bar, with a cement-cement interface between its two halves. Each cement-sandstone bi-material beam was prepared by first cutting a half beam (30 × 5 × 5 cm) out of a block of Bentheimer sandstone. The sandstone half-beam was then placed into the mould, and the other half of the mould was filled with cement slurry. The same composition of cement slurry was used throughout.

The prepared 60 cm beams were cured for at least one month at ambient pressure and temperature before the three-point bending test.

It was originally planned to prepare also cement-steel bi-material samples. However, the cement-steel interface strength turned out to be so low that it was not possible to remove the bi-material samples from the mould without inadvertently breaking the sample. A new mould was therefore made of wood. The mould could be completely disassembled by screws for easier sample retrieval after cement hardening (Fig. 4c). However, also with this mould, it was not possible to retrieve bi-material cement-steel samples without breaking them in half. Therefore, no cement-steel beam could be tested in three-point bending in this study.

It is customary to use beams with a pre-cut notch in three-point bending tests in order to evaluate the fracture energy rate. In our

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