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A new concept and finite-element study on dental bond strength tests

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ARTICLE INFO

Article history:
Received 18 February 2016
Received in revised form 9 May 2016
Accepted 16 July 2016

Keywords:
Finite element analysis
Adhesive test
Shear bond strength
Tensile bond strength
Lever-induced mold-enclosed shear bond strength
Bond strength

ABSTRACT

Objective. Numerous bond strength tests have been performed on dental adhesion experiments. Yet, the validity of these bond strength tests is controversial due to the name (*e.g.*, "shear" or "tensile") may not reflect to the true and complete stress situation, *i.e.*, assumed uniform shear or uniaxial tensile conditions. Thus, the aim of this study was to simulate and compare the stress distribution of and between shear bond strength (SBS), tensile bond strength (TBS), mold-enclosed shear bond strength (ME-SBS) and *de novo* lever-induced mold-enclosed shear bond strength (LIME-SBS) tests.

Methods. 3-Dimensional finite element method (FEM) was used on the dental resin-bonded surfaces (*i.e.*, titanium alloy, dentine and porcelain) interphased with adhesive layer (thickness 5 μm) to simulate the mechanical tests. For ME-SBS, both polycarbonate and stainless steel molds were used. For LIME-SBS, stainless steel levers and molds with lengths of 3 mm, 6 mm, 12 mm, 15 mm and 18 mm were used. The applied loads on these models were 50 N, 100 N and 200 N.

Results. De novo LIME-SBS test was the most optimal configuration to evaluate "shear" bond strength of adhesive in regards to providing significantly high and uniform shear stress as well as eliminating tensile stress at the interface. The conventional SBS test created very high tensile stress at the load area, whereas the TBS created optimal tensile stress but shear stress indeed co-exist. The ME-SBS test could also eliminate some of the tensile stress. Similar stress distributions pattern appeared on the Ti-adhesive models, the dentine-adhesive models and porcelain-adhesive models.

Significance. None of the bond strength tests could give purely "shear" or "tensile" bond strength, but LIME-SBS seems to be the best model to evaluate the bond strength under true "shear" mode.

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http://dx.doi.org/10.1016/j.dental.2016.07.005

1. Introduction

Most dental materials operate in the hostile oral environment. In the past decades, much advancement of dental materials has improved their functionality in terms of strength, biocompatibility, aesthetics and so on. It is necessary to evaluate the functionality of these new materials in many aspects *e.g.*, bond strength. To assess the quality of dental adhesives performance on the bond, bond strength tests are necessary. According to ISO 1942 (Dental Vocabulary) [1], "bond strength test" is defined as "*mechanical test designed to measure the stress required to disrupt the bond between two materials*". In clinical setting, the stresses for bonding may be comprised of various factors. It is inaccurate to assess overall bonding quality using any of the bond strength test, but at least predications could be made based on the bond strength test results.

Indeed, massive amounts of bond strength tests have been performed with regards to shear bond strength (SBS), tensile bond strength (TBS), micro shear bond strength (μSBS), micro tensile bond strength (μTBS), push out (PO), micro push out (μPO) and their several forms [2–16]. Usually, macro tests are simple to carry out compared to micro tests. TBS tests are more uniform at the interface and are similar to nominal strength [17]. In particular, shear bond strength test has been utilized for characterization of, *e.g.*, resin-to-resin [18], resin-to-metal [13,19,20], resin-to-ceramic [9], ceramic-to-ceramic [21], ceramic-to-metal [22,23], PMMA-to-metal [24], bondings. Prevalence of the shear bond strength test was high in laboratory testing, as the test does not require additional sample preparation compared to tensile bond strength test. Although "true" SBS is difficult to create and measure in conventional laboratory setting, this should possess as an important mechanical and physical property, *i.e.*, adhesive, of a material. For example, the push-out tests have been demonstrated as a method to test "true" shear bond strength [25,26].

In the conventional SBS test, usually a cylindrical adherent material is adhered to the adherend by adhesives (Fig. 1). A tool (*e.g.*, shear blade, chisel, metallic tape or wire loop) attached to the instrument crosshead could provide the load acting on the adherent among the test configuration (Fig. 2) at shear [27]. In many situations, the crosshead is usually applied at constant speed of 1.0 mm/min [3,6,13,28], although some other studies might also use other speeds, ranges from 0.5 mm/min to 5.0 mm/min [28,29]. A load transducer connected with the crosshead would record the force. Once in contact with the sample, theoretically the crosshead counterforce would gradually rise, initiating from 0 N to a nominal value until fracture the sample. Then, the final counterforce at fracture is reported. The maximum recorded load (*F*) divided by the bonded area (*A*) is noted as one SBS value (τ) data for one unique shear bond strength test configuration ($\tau = F/A$) [29]. In fact, under the conventional shear condition, the test configuration formed by the adhesive, adherent and adherend might not always fully in 'brittle shear' mode. Indeed, the 'ductile mode' and 'brittle-ductile mode' are also observed by shear motion that would incur the cohesive or mixed failures.

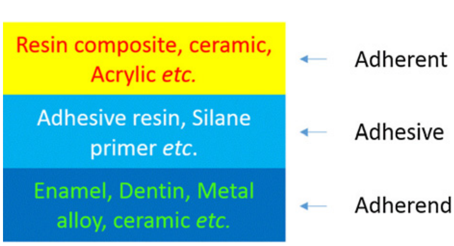

Fig. 1 – The schematic picture of adhesion in dentistry.

It should be noted that the clinic performances and basic material properties should be two different parameters [30]. The SBS should be considered as one mechanical property of the material. In contrast with the tensile bond strength test, the conventional SBS test has long been criticized for not be being appropriate or reliable to represent the so-called "actual" or "true" bond strength by shear at the bonding interface. The crack tip leading to the eventual fracture of the SBS test, could be caused by undesired high tensile stress, rather than the minimum required shear stress [30,31]. The load is wasted in creating a cohesive failure within one substrate (Fig. 2), rather than shear loading on the adhesive between the adherent and the adherend. Regarding the stress distribution, it has been revealed that the SBS test introduces stresses in shear that is non-uniform at the bonding interface as well as within the different substrates [32–34]. That is, geometry of SBS test is inappropriate to measure shear bond strength [33]. It has been also verified that the crack leading to eventual failure may have been resulted from a bending moment and high stress focused on the adherent (*e.g.*, resin) [35,36]. In this manner, a pre-mature failure is likely to occur. The same occurrence may also appear in μSBS tests [37,38]. So, a SBS test may not be a test that is driven by shear stress only, but also caused by vast tensile stress. An optimal approach to test authentic bond strength at shear is still to be discovered.

In a TBS test, the sample is under tensile force until fracture occurred. Similar to SBS, the TBS is calculated as the force at fracture over the bonded cross sectional area. The stress distribution of a tensile bond strength test may also be localized. In the finite element analysis (FEA) of a tensile bond test, it was shown that the stress concentration at certain sites of the adhesion area also appeared [39]. Yet, despite the TBS test is more appropriate in representing the bond strength in terms of tensile [38], there is no guarantee about TBS does not have any shear stress component. Furthermore, for laboratory preparation, the TBS requires the fine sectioning of a material which may lead to initial/eventual cracks in the sample, and might not easy to prepare specimen in, say, high strength materials.

Efforts have been made for restricting the undesired stress distribution in SBS test method. In some of the SBS tests, knife edge (chisel), stainless steel tape and orthodontic-looped wire were served as methods of loading [31,40]. Using these methods, the length of the cylindrical adherent stub could be decreased since the point of loading could get very close to the adhesion surface. Apparently, shear stress would be more evenly distributed and partially diminished the tensile stress. Thus, this seems to be an commendable approach that could improve the SBS test [32]. On the other hand, another rational approach, known as mold-enclosed shear bond strength (ME-SBS) test suggested by Van Meerbeek et al. [40], would be applying the mold to enclose the test stub, and the mold