A fracture study of the diametral compression test by means of high-speed photography

LARS EHRNFORD

Department of Dental Materials, Faculty of Odontology, University of Lund, Malmö, Sweden

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High-speed photography (2000 - 6000 pictures/sec) was used to register the fracture propagation process in gypsum specimens (diameter 40 mm, length 14 mm) loaded via 2 mm wide, strip-shaped paddings and under direct contact with plane press platens. With paddings in 3 out of 4 experiments the fracture, as it appeared on the first film frame, was asymmetrically located on the loaded diameter. In two direct-contact experiments the initial fracture had its widest part centrally and lateral fractures, of the «triple-cleft» type, appeared subsequent to the central fracture.

Smaller specimens (diameter 7, length 14 mm), manufactured in an investment compound (Ceramigold®) were tested by the use of plane and vaulted platens, giving the same width of the loaded area. With vaulted platens the fracture first appeared in a peripherical zone in 3 out of 5 experiments and with plane platens in 6 out of 11 experiments. In two thirds of all cases, where the primary fracture sign appeared peripherically, it appeared in an area immediately centrally of the compression zones. These fractures were probably peripherically initiated and thus non-valid. Specimen appearance after testing gave, however, no clear indication of a non-valid fracture.

Key-word: Dental materials; tensile test; dental investment material; dental stone

L. Ehrnford, Inst för odontologisk teknologi, Tandläkarhögskolan, Carl Gustafs väg 34, S - 214 21 Malmö, Sweden

The diametral compression test, originated by Carneiro 1947 (1), offers the advantage of being a simple method for measuring tensile strength, in which the same type of cylindrical specimens can be used as in regular compression strength tests. One further advantage offered by this method is that the fracture starts centrally in the specimen, and thus the tensile strength can be measured without any influence from defects located in the surface layer of the specimen (6). This is due to the fact that the fracture is initiated by tensile stresses across and normal to a central part of the loaded diametral plane. However, the way in which the load is transmitted to the specimen is of crucial importance as to whether this will actually happen. The distribution of load in the contact area also determines the magnitude and the extension of the tensile stresses in the diametrical plane; thus, they can influence the load required for fracture.

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Ideally the test method should, besides meeting the request for standardized loading conditions, also provide a load distribution over as small a surface as possible without risking, at the same time, other types of fractures than the adequate tensile fracture. In previously used test methods the specimens have usually been loaded via interposed wide or strip-shaped paddings (5, 7), and when specimen flattening was considered sufficient – based on fracture appearance – with direct press-platen contact (2, 8).

In previous investigations the effects of load distribution variations were studied in view of the fracture load (3) and the distribution of stresses (4). Viewed together, these investigations indicate the possibility of a peripherical initiation of the fracture when the load is insufficiently distributed in the contact area; and this occurs without any significant change of the fracture pattern configuration, which, according to earlier statements (7), would take place. The purpose of the present investigation was to try to register the process of fracture propagation when contact surfaces were small by means of high-speed filming.

MATERIALS AND METHODS

Disc-shaped gypsum specimens with a diameter of 40 mm and a length of 14 mm were manufactured with a water/powder ratio of 0.30 in accordance with a previously described method (3). A smaller specimen type with the same width (14 mm) was manufactured of an investment compound for casting high-melting alloys (Ceramigold®, Whip-mix Corporation, Louisville, KY., USA). The investment compound was mixed in conformity with the instructions of the manufacturer (water/powder 0.16) and was moulded in moulds of PTFE (Teflon®). The mould cavity was rotation symmetrical and cylindrical with open end surfaces. One opening was closed by means of a glass pane. The compound was cast in the mould under simultaneous vibration so that a 3–5 mm surplus was created. After setting (for 2 hours) the specimen was transferred to a ring-shaped holder of brass, by means of which the surplus was removed and the length was ground down to 14.0 mm by abrasive paper. Before use the specimens were stored for one week in a relative humidity of 50–55 % and a temperature of 20 - ± 1°C.

Two randomly selected generatrices were marked which were later to constitute the first line of contact with the press platens of the test device. Using a microcator it was possible to ensure that their deviation from parallelism remained less than 5 micron. In order to ensure a high degree of accuracy to the testing equipment (Alvetron®, Lorenzen & Wettres, Stockholm), the press platens were directed by means of a special device (Fig. 1). Two parallel columns, solidly attached to the bottom platen, control the top platen via a ball bearing. Thereby the deviation from parallelism between the used parts of the platens could be kept below 5 micron.

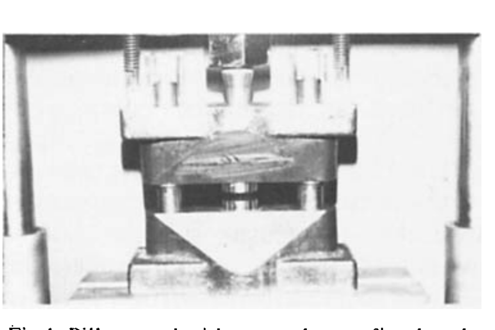

Fig 1. Pillar stand with press platens, fitted to the testing device.

The bigger gypsum specimens were fitted between the platens by direct contact and by strip-shaped paddings of a width of 2 mm in accordance with a previously described method (3). In order to make it possible to get a predetermined ratio between the width of the loaded area (a) and the specimen diameter (d), and in order to ensure a uniform distribution of the load over a defined loaded area, inserts of aluminium were manufactured for the small specimen type (Fig. 2). These were symmetrically orientated by means of a separate control device (Fig. 2). This makes it possible to give the inserts a reciprocally correct relationship in the vertical plane by pressing rods into wedge-shaped grooves in the lateral surfaces of the inserts. The rods just contact the specimen when it is correctly centered. The control device was removed when the specimen had been fixed between the press platens. The inserts contact surface towards the specimen was vaulted and had the same radius as the specimen. The width of the loaded area was adjusted in such a way that it should result in a ratio of 0.10 (a/d) to the specimen diameter. The purpose of this was to obtain approximately the same loaded area as in the case of direct contact with the press platen. In the preparatory experiments the same type of vaulted inserts were used which gave a 0.20 a/d. a/d at direct contact was measured by relieving a few specimens within the variation range of the fracture load, but before fracture. As the platen had been inked the width of the loaded area could be measured on the colored imprint of the specimen.

For the film shooting a «Type 16» Hitachi high-speed motion analysis camera (Hitachi Ltd, Tokyo, Japan) was used, with a lens of type Nikkor 105 and a Kodachrome II A film. The camera was focused on one end surface of the specimen. For lighting a halogen spotlight of type Hedler de luxe 2000 was used (0. Hedler 6251, Rundkel-Ian, West Germany). Two 1,000–W lamps bilaterally irradiated the specimen end surface in the horizontal plane from a distance of approx. 25 cm and at a 45° angle of incidence.

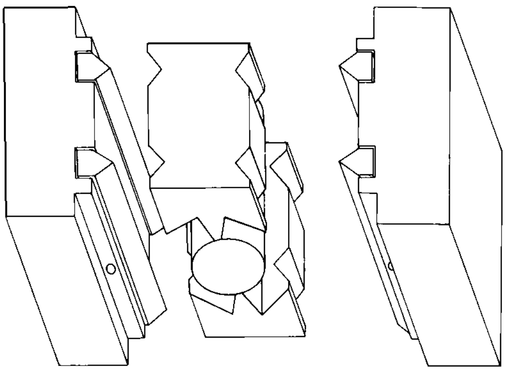

Fig. 2. Inserts to bring about an equalized distribution of the load in the loaded area as well as a control device for centering the specimen.

PREPARATORY EXPERIMENTS

In the previous experiments (3) the material consisted exclusively of dental stone. For the present study it was considered desirable to examine a somewhat less brittle material so as to bring about a slower and more easily recordable crack propagation process. For that purpose an embedding material for dental high-temperature casting was chosen (Ceramigold). That the crack propagation process appeared slower was verified by preparatory experiments. Specimens in embedding compound were then mounted in such a way that the press platens of the testing device actuated through soft paddings consisting of multilayered paper and, next to the specimen, a thin steel blade in a previously described manner (3). The thickness of the paper layers was adapted so as to give a 0.2 a/d at fracture load. In 8 out of 10 fractures the first sign of the fracture could then be traced to the central one-third of the loaded diameter.

When the corresponding experiments were carried out with gypsum specimens (water/powder ratio 0.30) with the same dimension and load parameters, the fracture propagation process could not be registered. So for the following experiments a bigger type of gypsum specimen was chosen.

In order to make sure that the specimens in the embedding compound showed a similar correlation between fracture load and loaded area as the one which had previously (3) been registered for gypsum, specimens were tested which were loaded both by a/d 0.1 through direct contact and through a vaulted insert, and also by a/d 0.2 through soft and wide paddings of the previously described kind (3) and through vaulted aluminium inserts. The increase of a/d entailed an approx. 30 % increase of the fracture load. However, the different types of loadings at the same a/d, did not result in any significant differences in the fracture load.

EXPERIMENTS

Film-shooting was made of the specimens in investment compound, both in load by direct contact with the press platens, and with vaulted inserts (a/d 0.10) fitted. Gypsum specimens were mounted besides in direct contact (a/d 0.07) with the press platens, also through strip-shaped inserts of paper of a width of 2 mm (a/d 0.05) in accordance with a previously described technique (3).

The load was applied at a rate af approx. 40 N/sec for the small and approx. 200 N/sec for the big specimen type. Not until 1–2 seconds before camera start were the spotlights turned on so as to avoid any unnecessary heating of the specimen. The camera was triggered by an impulse from the testing machine at a preset load. In order to reduce the number of precocious film starts, the starting was coupled to the top part of the variation range of the fracture load. Film velocity was approx. 2,000 pictures per second for the small specimens and 4,000–6,000 pictures/second for the gypsum specimens.

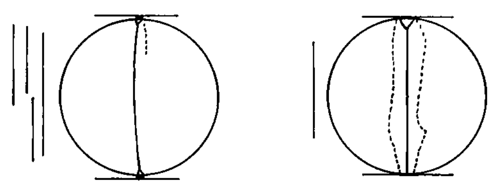

Fig. 3. Appearance of the central fractures and the lateral fractures (marked with lines) in gypsum specimens loaded via strip-shaped padding (a) and with direct contact (b) with the plane press platen. Vertical lines mark the visible fracture line, in the first fracture picture, for each specific experiment.

RESULTS

Fig. 3 a shows the fracture pattern for 4 experiments with gypsum specimens and strip-shaped padding, and Fig. 3 b shows 2 experiments with gypsum specimens and direct contact. In the strip insert cases the diametrical fracture appeared throughout with its widest part within the peripherical fourth of the specimen. In 3 out of 4 cases extension was initially assymetrical. In the direct-contact experiments the diametrical fracture appeared in both cases with its widest part centrally, and in one case with a symmetrical extension initially, in a central part of the loaded diameter. In the second case it was not possible to follow the extension of the fracture in the first film frame on account of superficial fragments of the specimen coming loose above the loaded area. Lateral fractures, of the triple-cleft type (Fig. 3 b), appeared in both the load cases after the diametrical fracture.

As regards the specimens in the embedding compound the first sign of fracture formation could in most cases be located to a minor zone in the end area. Table 1 shows at what frequency the fracture first appeared in the different sections of the end area. Fig. 4 shows the division into zones. For the vaulted inserts the first crack sign appeared centrally in zone C in 1 of a total of 5 cases. The plane press platen gave a corresponding result in 2 out of a total of 11 cases. In one case of vaulted contact area and in 3 cases of plane contact area, the fracture appeared in several zones simultaneously. In no case was it possible to locate the fracture sign to zone B exclusively, whereas it was to be found in the peripherical zone A in 3 (vaulted) and in 6 (plane) cases respectively. Out of them, two thirds of both types were located to zone A_0. The completely developed fracture ran in all the cases within that section of the end area which is covered by zones (Fig. 4), and it finished – unilaterally or bilaterally – in triangular fragments in the same way as is illustrated for the gypsum specimens (Fig. 3).

The fracture load did not differ significantly for the two load types.

One feature which the two secimen types had in common was the fact that

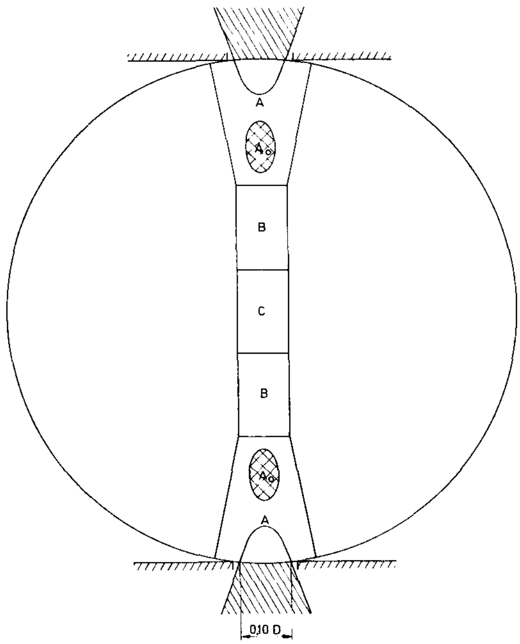

Fig. 4. End area of the specimen divided into zones.

the fracture pattern differed only as regards the lateral fractures between direct-contact specimens and the specimens with a limited loaded area. In both end areas the fracture pattern was similar throughout.

Not fully developed diametrical fractures were in most experiments registered in only one film frame. They then appeared as such fine lines that they did not permit a meaningful photographic reproduction.

DISCUSSION

The results for gypsum specimens with strip-shaped padding make it evident

Table 1. *Distribution of the experiments as regards the zone in which the first visible part of the crack appears*

Zone	A	(Ao)	B	C	Simultaneously in several zones
Vaulted platen (a/d 0.10)	3	(2)	0	1	1
Plane platen (a/d 0.12)	6	(4)	0	2	3

that the fracture, in the first picture, in most cases appears asymmetrically across the diameter, having its widest part in the peripherical fourth. As regards specimens of embedding compound, more than half of the experiments show that the first appearence of the fracture is located in the peripherical fourth of the loaded diameter. Out of those cracks which appeared within the peripherical zone A none could be observed starting right from the periphery of the end area. On the contrary, most of the cracks first emerged within the zone A_0, which is probably to be found centrally by the point of the wedge-shaped compression zones which are formed under the loaded area.

FEM analyses indicate that considerable tensile stresses can be generated peripherically at the borderline of the loaded area in the case of small a/d ratios (4). However, as was pointed out before, no fracture initiation could be observed on that point. But it was conclusive from the experiments that the fracture opening has to take on a certain size (a rather limited one, though) in order to be registered. So, in the initial stage an actual fracture might escape registration in the same way as the full extension of a fracture may be underestimated. Consequently it is possible that the fracture is initiated by the above-mentioned peripherical tensile stresses at the borderline of the loaded area and that the compression zones are thereby forced like wedges in a central direction; as a result a major and visible increase of the fracture width does not appear before the area next to and centrally by the compression zones. Registrations which locate the first sign of fracture formation to zone A, and especially zone A_0, may for this reason indicate a peripherical fracture initiation.

All the combinations of specimen and load method turned out, in this and in a previous investigation (3), to give fracture loads which fall by 30 % or more, below those fracture load values which can be obtained when the loaded area is magnified by means of a soft or vaulted insert.

This occurred without the highest admissible value a/d 0.2 being exceeded (6). Except for the two gypsum specimens having direct contact with the platens, an assymmetrical fracture propagation process appeared in most experiments. The greatest diametrical tensile stresses appear, however, centrally also at small a/d (4). So, an adequate testing procedure would also in most cases entail a centrally initiated and symmetrical fracture. The comparatively low fracture load and – in most cases – the assymetrical location of the fracture are, consequently, phenomena which contest a central initiation of the fracture.

The experiments provide a basis to assume that there is a lower limit for the extension of the loaded area, which limit it is possible to fall below, with or without the use of limiting paddings. Below this limit non-valid and probably perpherically initiated fractures will result. This will, however, not affect the appearance of the specimens after fracture to any significant extent. Furthermore, the experiments support the assumption that so-called «triplecleft» fractures originate subsequent to continued charge on the halves (7).

Summing up, it could be concluded that the characteristics required from a centrally initiated and symmetrical fracture type are not fulfilled in the results obtained for specimens with small a/d. However, the assymmetric fracture propagation indicates, together with the comparatively low fracture loads, that the fractures are non-valid and probably peripherically initiated.

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