Specimen geometry in uniaxial tension test of concrete

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ABSTRACT: Tension softening behavior is essential to analyze and understand the fracture process of concrete and concrete structures. Many test methods of uniaxial tension for concrete have been investigated for 40 years to obtain tension softening behavior. The test methods were different in specimen geometry, loading process and control of secondary flexure. This study concerns the specimen geometries such as prisms, cylinders and dog-bone types with or without notches. In some types of specimens, we cannot obtain an exact tension softening behavior and tensile strength. However, inappropriate specimens have been adopted even in recent investigations, because of several misunderstandings in the test methods. Such misunderstandings are discussed and clarified referring to experimental evidences, numerical simulations and theoretical considerations. Considering also the ease of specimen handling, it is concluded that a notched prism should be recommended among all the specimen geometries.

1 INTRODUCTION

The knowledge of the tension softening process of concrete is essential to analyze fracture behavior and to estimate concrete properties. One of the best ways to investigate the tension softening process is testing under uniaxial tensile loading because of the simultaneous investigation of both tensile strength and softening curves from an identical specimen. Additional tests or calculations, such as inverse analysis, are not required for the uniaxial tension test.

However, the test procedure is still subject to several misunderstandings concerning the effects of notches, secondary flexure, boundary conditions and specimen geometry. Due to theses misunderstandings many inadequate test procedures have been proposed over the past 40 years.

In this paper, the misunderstandings in uniaxial tension test are discussed. The appropriate specimen geometry for the test is investigated, referring to some experimental evidence and numerical simulation results.

2 TENSILE BEHAVIOR OF CONCRETE

It is essential in the uniaxial tension test to apply tensile load to the specimen, making effort to avoid load eccentricity in order to prevent unexpected flexure. However, unexpected flexure still occurs because of the heterogeneity of concrete, even if there is no eccentricity in the applied load. When a rectangular prism of concrete is subjected to tensile load without any load eccentricity, the weakest zone in the specimen surfaces is damaged first. Then, the damaged zone, called fracture process zone or softening zone, is softened and elongated more than the other part of the section. This elongation is the cause of unexpected flexure as shown in Figure 1. This flexure is denoted as secondary flexure. The damaged zone elongates more and becomes weaker according to the increase of applied load, unless any countermeasure is adopted. It means that the second-

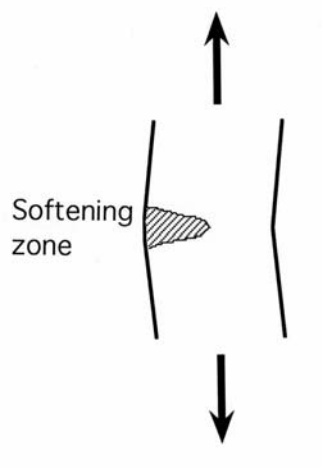


Figure 1. Secondary flexure

ary flexure becomes larger and larger, unless artificial elimination is adopted.

The secondary flexure is very harmful for the test, because it produces a strain gradient in the damaged section, and consequently tensile stress distribution in the section is quite different from uniform. In other words, the flexure produces a big error in the calculated tensile strength, because tensile strength is calculated by dividing the maximum load by the area of the damaged section. This non-uniform stress distribution is shown qualitatively by Hordijk et al. (1987) using a simple illustration and also shown quantitatively by Akita et al. (2000) using a detailed figure based on finite element analysis combined with the fictitious crack model proposed by Hillerborg (1978). Figure 2 shows the finite element model for the analysis when the notch depth is 5 mm. The notch is adopted in order to produce heterogeneity of concrete in a simple way. Figure 3 shows the bi-linear tension softening curve used for the calculation of cohesive stress in the fictitious crack. The bi-linear tension softening curve was proposed by Rokugo et al. (1989).

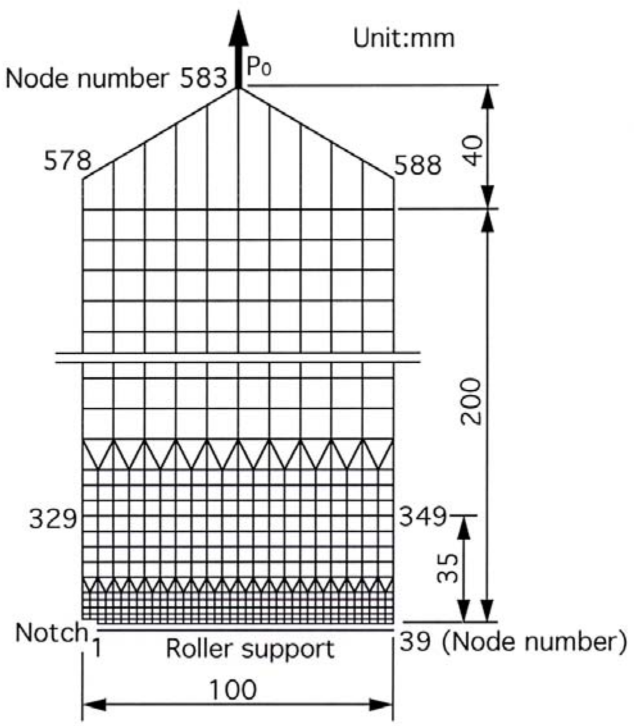


Figure 2. Finite element model when secondary flexure is left

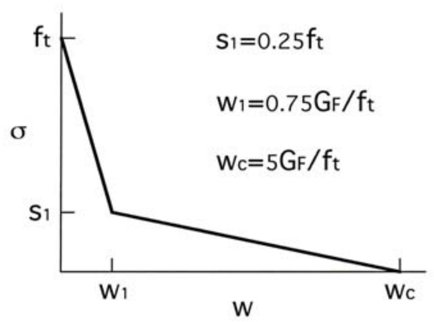


Figure 3. Tension softening curve

Figure 4 shows the obtained stress distributions in the damaged section of a prismatic specimen. The stress σ was expressed in terms of the ratio to tensile strength f_t. The corresponding applied load P is expressed by the ratio to the true peak load P_{true}. It is assumed that P_{true} is produced when the entire ligament section is subjected uniformly to the stress equivalent to tensile strength. The numbers along the curves indicate the node numbers in the finite element model within the notched section where the propagating fictitious crack tip reaches at the various load levels.

Because of stress concentration, the tensile stress at the notch tip reaches the tensile strength first during application of the load. Then, the damaged zone develops from the notch tip and spreads to the opposite side as the applied load increases. In the fracture process zone, tensile stress, called cohesive stress, depends on the degree of damage. Hillerborg et al. proposed the fictitious crack model to express the degree of damage by the crack width. It means the larger the crack opening displacement (COD) of the fictitious crack, the larger the damage of the position. The tension softening curve expresses the relationship between COD (w in Figure 3) and cohesive stress (σ in Figure 3). We can see from the curve the decrease of cohesive stress according to the increase of COD or the increase of damage.

When the fictitious crack tip comes to nodal point 3, the cohesive stress in the fictitious crack reduces little from the tensile strength and the remaining section is still subjected to lower stress because the applied load is still small. When the crack tip reaches node 19, the

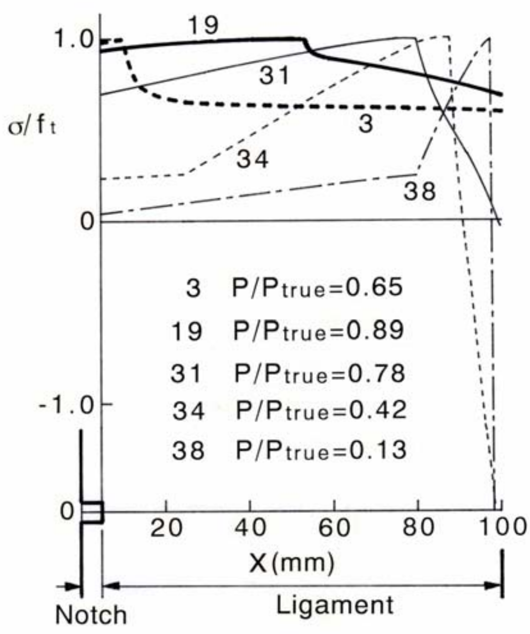


Figure 4. Stress distributions when secondary flexure is left

peak load occurs and the distribution consists of a plateau along one half of the entire ligament and a gradual decline along the other half. The corresponding peak load is about 11% less than the true peak load in this case. The peak load reduction is more serious when a deep notch is adopted for the model, corresponding to a larger secondary flexure occurrence.

When the fictitious crack reaches node 31, the stress level near the crack tip is maintained at tensile strength, while that near the notched side is reduced significantly. Interestingly, the stress level ahead of the crack tip drops so drastically that the opposite end of the ligament starts to compress. The tensile stress drop ahead of the crack tip is produced by bending compressive stress superposed to tensile stress produced by the applied load. When the fictitious crack reaches node 34, the bi-linear cohesive stress distribution is observed in the softening zone. It means that COD near the notch becomes so large that the stress versus COD relation is expressed by the second branch of the bi-linear model for the tension softening curve. When the fictitious crack reaches node 38, the same happens for most of the section. The opposite ligament end is subjected to a tremendous compressive stress which is beyond the graph area and eight times of the maximum tensile stress in this case. Not only the peak load reduction is serious, but also the stress distributions produced by the secondary flexure are quite different from the uniform one at the peak load. This is the reason why secondary flexure should be eliminated in the uniaxial tension test.

Figure 5 and 6 show load(P)-deformation(δ) curves from experiments when secondary flexure is eliminated or allowed to develop freely, respectively. In these Figures, ch-2 and 4 indicate the mutually opposite side face. As the two curves coincide well, the two opposite side deformations are always nearly equal, i.e. secondary flexure is well eliminated in Figure 5. In Figure 6, the deformation in ch-2 increases monotonically, whereas that in ch-4 first increases and then changes to decrease and finally comes to compression. This behavior is consistent with the stress distributions shown in Figure 4.

When secondary flexure is eliminated in a uniaxial tension test of concrete by using an un-notched specimen, two or three flexures in opposite directions appear and develop to multiple cracks. Figure 7 shows an illustration of such an experiment which uses a rectangular prism and observes surface deformations on four side faces by means of 12 strain gauges. When the maximum deformation is observed for example in gauge 5, an adjusting moment is applied in order to eliminate the secondary flexure observed as the difference between gauge 5 and 7. After the adjustment, the maximum deformation appears for example in gauge 3 contrary to the previous step. If additional adjustment is applied in order to balance the maximum deformation in gauge 3 to the opposite side, the deformation of gauge 5 becomes again the maximum one. This means that we cannot eliminate secondary flexure by using an un-notched prism. Multiple cracks are the result produced by a combination of two or three secondary flexures. The cracks also appeared in the case of Heilman's experiment as reported by Hordijk (1989). Heilman performed the test eliminating secondary flexure by using three actuators even 40 years ago, but he could never realize a uniform distribution of tensile stress in the cross section because of the occurrence of multiple cracks.

A reliable method to avoid multiple cracks is to adopt notches and to adopt a relatively short measuring length of deformation. The recommended specimen is a rectangular prism with notches on four side faces. In this specimen, not only the shape but also measuring of deformation and calculation of COD are simple. One big issue was whether stress concentration due to the presence of notches prevents to obtain exact tensile strength or not. As the authors already reported and solved (2002), it is a misunderstanding that the stress concentration due to the presence of notches affects the measured tensile

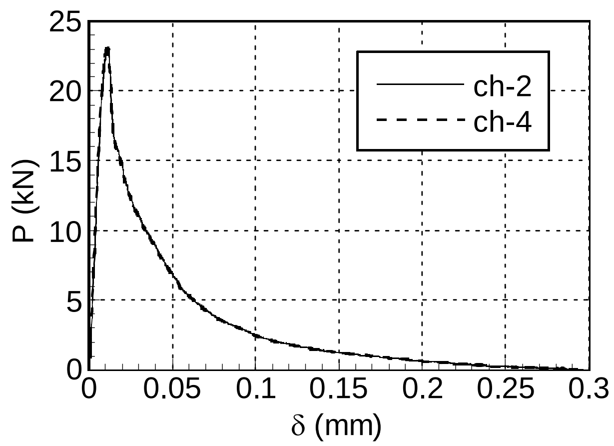


Figure 5. P-δ curves when secondary flexure is eliminated

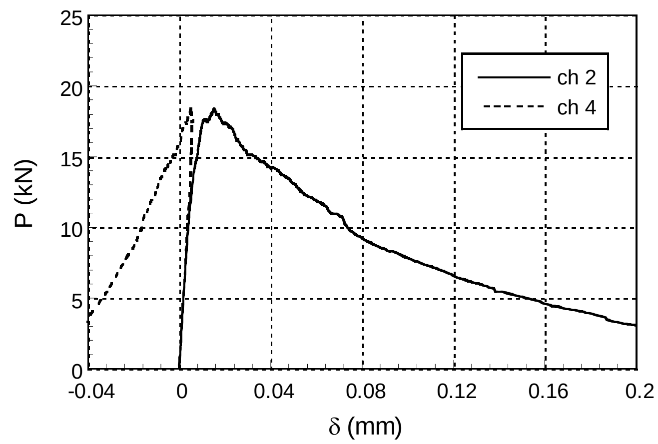


Figure 6. P-δ curves when secondary flexure is left

strength and we cannot obtain the exact value of tensile strength by a notched specimen.

3 NOTCH EFFECT

Figure 8 shows the finite element model for the analysis of a notched prism when secondary flexure is eliminated. Only a fourth of the specimen is modeled because of the dual symmetries against the vertical and horizontal center axis of the specimen. Figure 9 shows the stress distributions of the notched section in the specimen with respect to three levels of applied load. Because of the strong stress concentration caused by the notches, the stress level near the notch tip reaches the tensile strength even at low loading such as when P/P_{true} = 0.35. As the load increases, a fictitious crack that models the softening zone (fracture process zone) develops and expands from the notch tip towards the center. The size of COD within the fictitious crack is so small that each cohesive stress within the zone reduces little from the tensile strength. When the fictitious crack tip reaches node 4 and P/P_{true} becomes 0.79, the cohesive stress in the crack is almost equal to the tensile strength and the stress in the middle part is still smaller than the tensile strength. When the crack tip reaches the specimen center, i.e. node 19, P/P_{true} becomes 0.99 and a single plateau across the whole cross section is created, resulting in strain softening of the entire cross section. This means that the stress concentration diminishes at peak load and that an almost uniform cohesive stress that is nearly equal to the tensile strength is distributed in the ligament area. The peak load is reduced little, only 1 % compared with the true peak load, in spite of the existing notches. So the accurate peak load or consequent tensile strength is obtained by using a notched specimen in a uniaxial tension test of concrete.

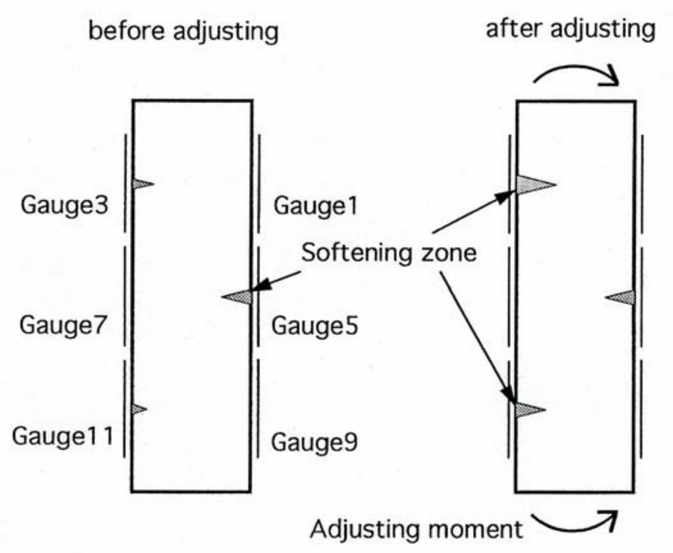


Figure 7. Multiple cracks formation

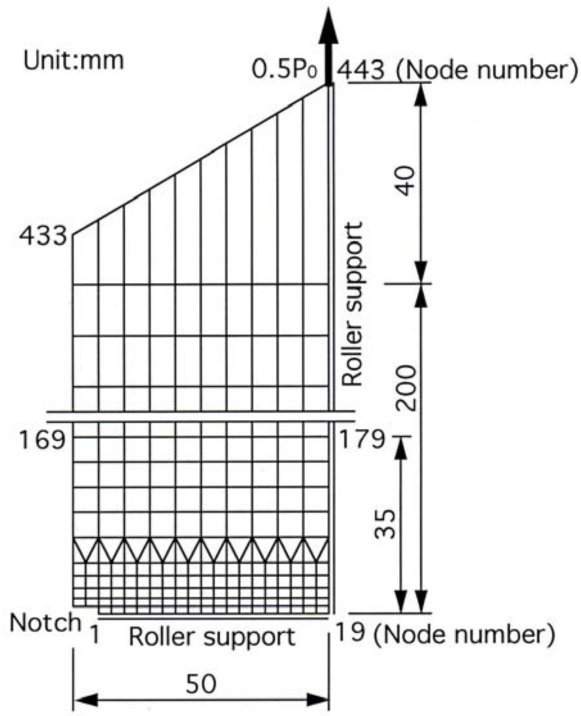


Figure 8. Finite element model when secondary flexure is eliminated

4 ADDITIONAL NOTCHES

When the uniaxial tension test of concrete is performed using a notched prism and eliminating secondary flexure, duplicate cracks sometimes occur, as shown in Figure 10 for a double notched specimen. The duplicate cracks are also harmful, because the measured fracture energy is doubled since two

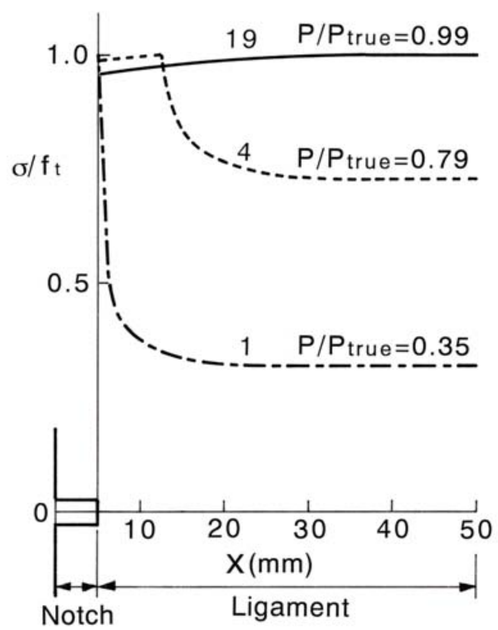


Figure 9. Stress distributions when secondary flexure is eliminated

cracks are produced. In order to avoid the duplicate cracks, additional notches should be made on the other two faces. The additional notch is called the guide notch and the previous notch is called the primary notch. These notches are shown in the cross section of prism in Figure 11 where the dimension of the cross section is 100x100mm.

5 NOTCH DEPTH

In a uniaxial tension test, deep notches are favorable to avoid failure outside of the notched section. On the other hand, deep notches rather waste concrete materials. Thus, the knowledge of the shallowest notch to break the specimen in the notched section is useful for effective use of concrete. In order to find the shallowest notch depth, three notch depths were examined using 34 rectangular prisms of 100x100x400mm. Table 1 shows the result obtained using double notches, i.e. without guide notches. There is a tendency the deeper the notch adopted, the higher the rate of success. However, the shallowest and reliable notch depth could not be found in this experiment. In spite of the result, the breaking occurred always in the notched section in the later test adopting the same notches as shown in Figure 11. These tests were performed using the maximum aggregate size of 20mm and several strength levels of concrete. Considering an easy preparation and application to different mitures,10mm depth on all four side faces should be a recommendable one.

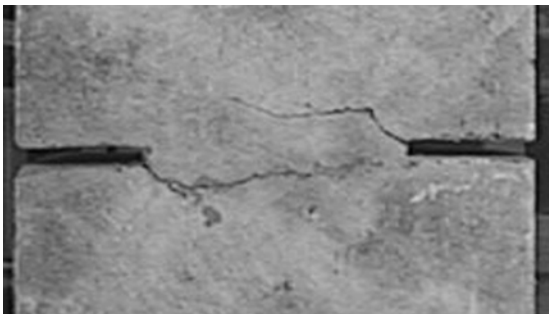


Figure 10. Duplicate cracks

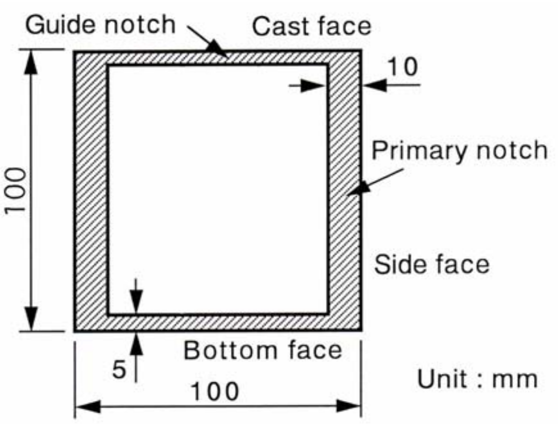


Figure 11. Cross section of the specimen

6 DISCUSSIONS OF SPECIMEN SHAPE

The six specimen shapes shown in Figure 12 and 13 have been mainly examined since 40 years. Among them, a rectangular prism with notches is the recommended specimen shape, because it allows easy casting, easy measuring of four side deformations and easy calculation of COD from the measured deformations. Shallow notches are also recommended, because small difference of the ligament area and the whole sectional area is desirable for easy calculation of COD.

Plate type specimens in Figure 12 are not recommendable. Because, secondary flexure can not be avoided by adopting this shape unless artificial elimination of the flexure is executed. This shape unnecessarily wastes much concrete except in the case when size effect is investigated.

Cylindrical cast specimens in Figure 12 are also not recommendable. Although the specimens are almost isotropic in the plane perpendicular to the cylinder axis, this does not mean that a secondary flexure cannot occur in the specimen, because the crack arrest effect by aggregates is not equal in all directions in the cross section of the specimen. When cylindrical cast specimens are used for a tensile test, they will usually be stretched along the casting direction, i.e. the weakest direction, because the bleeding water makes water films beneath the coarse aggregates. Figure 14 shows the comparison of the tensile strength obtained from horizontally

Table 1. Rate of success to break in notched section

Notch depth (mm)	Number of success	Total number	Rate of success (%)
5	4	9	44
7.5	7	10	70
10	9	15	60

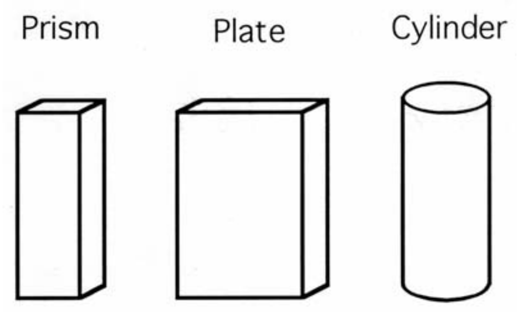


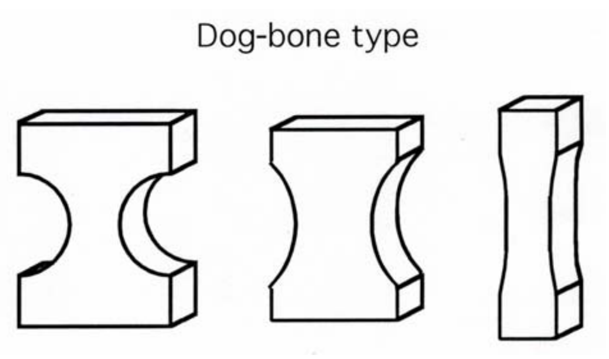
Figure 12. Specimen geometries (1)

casting prisms (usual casting) and vertically casting prisms (artificial casting). The specimen numbers #1 to #5 are put in order of tensile strength. The numbers with “D” indicate the ages of concrete at the testing date. The specimens cast vertically always show lower tensile strength despite their higher ages and they are 13% lower in average than that of the specimen cast horizontally. This means that cylindrical cast specimens provide a specific strength related to the cast direction which is considerably lower than that of the other two directions. Cylindrical cast specimens should therefore be restricted to the special use when tensile properties of concrete along the cast direction are required.

The dog-bone type (c) in Figure 13 is equivalent to a rectangular prism when the part of the smallest sectional area has enough length. It is a necessary shape when end gluing is too weak to use a simple prism.

Dog-bone type (b) is not recommendable. Multiple cracks also appear in the specimen of this type as Planas (1998) reported. Thus, this type unnecessarily has a complicated shape.

In dog-bone type (a), the possibility of multiple cracks occurrence is relatively small. However, the position of cracked section will vary or crack will incline around the mid-height of the specimen. The main weak point of this specimen is the complicated calculation of COD from the measured deformation between some points. The complicated specimen shape is also one of weak points.



(a) (b) (c)

Figure 13. Specimen geometries (2)

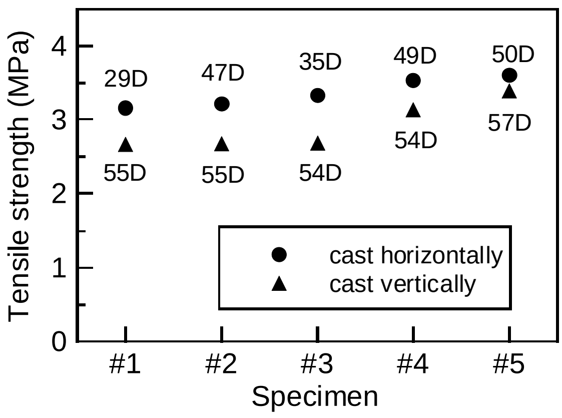


Figure 14. Comparison of tensile strengths

7 CONCLUSIONS

A rectangular prism with notches is the recommended specimen shape for uniaxial tension test of concrete.

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