Experimental and model studies on the Modified Tension Test (MTT) - a new and simple testing method for direct tension tests

R.J. Plinninger
Dipl.-Ing. Bernd Gebauer Ingenieur GmbH, Munich, Germany

K. Wolski, G. Spaun
TU München, Lehrstuhl für Allgemeine, Angewandte und Ingenieur-Geologie, Munich, Germany

B. Thomée, K. Schikora
TU München, Fachgebiet Baustatik, Munich, Germany

ABSTRACT: The "Modified Tension Test" represents a new and innovative approach to the laboratory research of the uniaxial tensile strength. The test features a cylindrical specimen of special geometry so a unidirectional, direct tensile stress field is created in the sample. The test may easily be carried out in any standard testing machine to test the Unconfined Compressive Strength (UCS). The presented results evaluate the MTT as an easy-to-carry-out laboratory testing method, which on the one hand shows a good ratio of the required testing equipment and demands for the testing material. On the other hand, it provides a realistic value for the direct tensile strength of a rock or concrete sample. From the experience of this program, some practical suggestions are also made on testing circumstances such as sample geometry, sample preparation and documentation of the test result.

1 PROCEDURES FOR TESTING THE TENSILE STRENGTH OF ROCK AND BUILDING MATERIAL

In addition to the unconfined or triaxial compressive strength and deformability, the tensile strength is one of the most important parameters for the mechanical description of a rock or building material.

Unfortunately testing of direct tensile strength is a rather difficult task with a lot of technical problems: If mechanical clamps are used to fix the sample, problems of point loads and uneven stress distribution in the sample may arise. Especially in hardrock testing, the use of adhesives is a problem. And even when these problems are solved, complex bending tensile stresses can occur during failure, when an initial crack on the one side of the sample is propagated to the other side. Additionally, testing systems that can be used for direct tensile tests are not as widely available as standard systems for testing compressive strength. Therefore direct tensile tests are used rather infrequently in the field of rock mechanics and geotechnical engineering (FECKER & REIK, 1996, p. 269f; PRINZ, 1997, p. 49).

In contrast to this, indirect testing procedures, such as the Brazilian, point load or bending tests are widespread throughout the world. A number of standards such as the DIN 1048 German standard and testing recommendations such as DGEG (1982, 1985) and ISRM (1978, 1985) deal with these tests and provide a good background for comparable test results. Nevertheless, comparisons between direct and indirect tension tests are difficult and empirical equations have to be used for such purposes.

The presented paper summarizes results of a dissertation at TU München, Lehrstuhl für Allgemeine, Angewandte und Ingenieur-Geologie (chair for general, applied and engineering geology; WOLSKI, 2002) and finite element studies that were carried out at the TU München, Fachgebiet für Baustatik (Professorship for the Analysis of Civil Engineering Structures, Faculty for Civil Engineering and Surveying) in the course of a PhD thesis on the modeling of steel fiber reinforced concrete in structural mechanics (THOMÉE, in preparation)

2 INTRODUCING THE MODIFIED TENSION TEST (MTT)

The "Modified Tension Test" (MTT) dealt with in this paper was developed at the institute for rock mechanics and tunneling at the TU Graz, Austria. Basics of the testing principle and testing requirements were presented at the EUROCK 2000 symposium in Aachen, Germany by BLÜMEL (2000). The test uses a simple, cylindrical specimen that is over cored from the top and bottom by two axial core drill holes with different diameters (Figure 1). After placing a load plate (top) and load ring (bottom), the sample is then loaded in a standard testing device for compressive testing. Failure occurs by direct tension in the area in between the both overlapping core drill holes ("tension zone").

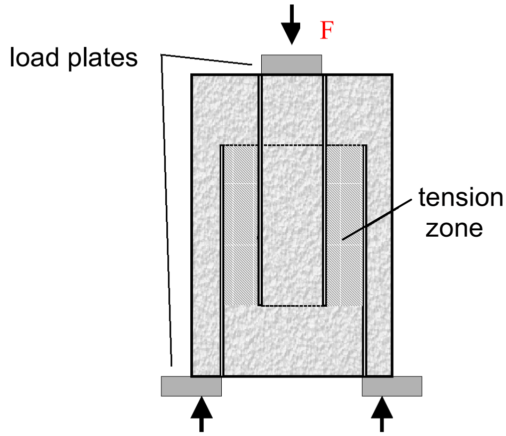


Figure 1: General testing layout and sample geometry for the Modified Tension Test.

The MTT tensile strength σ_{MTT} is calculated from the maximum compressive load F_{max} and the area of the tension zone A_{TZ} which depends on the radius r_1 and r_2 of the core holes (Equation 1):

$$\sigma_{MTT} = \frac{F_{\max}}{A_{TZ}} = \frac{F_{\max}}{r_1^2 \cdot \pi - r_2^2 \cdot \pi} \quad (1)$$

mit:	σ_{MTT}	MTT tension strength	[MPa]
	F_{max}	failure load	[N]
	r_1	radius of the larger core hole	[mm]
	r_2	radius of the smaller core hole	[mm]

Suggestions made by Blümel to format samples include a sample diameter of > 100 mm, a length-diameter ratio of about 1.5:1 and special formatting of the sample faces according to UCS testing standards.

3 COMPARING DIFFERENT TENSION TESTS

As an example for the wide range of values that can be obtained from different testing procedures, this chapter presents results from a series of tests on a homogenous and isotropic rhyolithe from the Rennsteig tunnel project at Oberhof in Thuringia, Germany (Wolski, 2002; see Figure 2, Table 1). The samples from this fine to medium grained and medium weathered rock are characterized by hypidiomorphic feldspar minerals that are embedded in a very fine grained quartz matrix.

As further explained in chapter 5, the tensile strength values obtained from the MTT are very close to the theoretical tensile strength of the rock material. In comparison with the MTT, other test results are up to about 90 % (Brazilian test), 110 % (point load test) or even about 260 % (bending test) higher than the direct uniaxial tensile strength of the rock material.

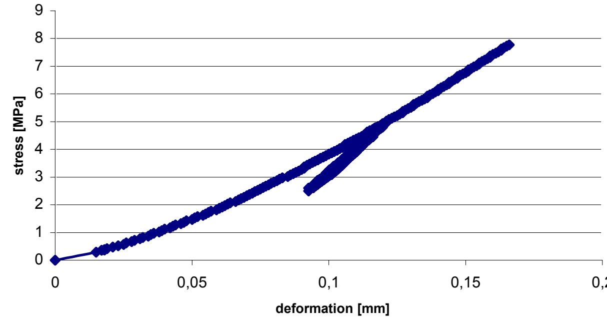


Figure 2: Example for a stress deformation curve of an MTT test on rhyolithe.

Table 1: Testing results of rhyolithe samples.

Modified Tension Test	3.8 ± 0.97	MPa
Brazilian Test *(acc. to DGEG 1985, ISRM 1978)*	7.2 ± 1.6	MPa
Point-Load-Test *(acc. to DGEG 1982, ISRM 1985)*	8.0 ± 1	MPa
Bending Test *(acc. to DIN 1048)*	13.5 ± 1.5	MPa
Unconfined Compressive Strength	102.3 ± 9.1	MPa
Young´s Modulus	25.8 ± 2.1	GPa
Destruction work W_Z	204.1 ± 21.8	kJ/m³

4 DEFORMATION MEASUREMENTS

In order to get an idea of probable bending moments in the sample, axial and lateral deformation was monitored during some tests. Realistic deformation measurements were also useful for adapting the finite element model presented in chapter 5.

The measured deformations were very low, with a maximum axial deformation of about 0.2 mm, +0.004 mm lateral deformation at the bottom and –0.001 mm lateral deformation at the top of the sample (Figure. 3), which is only a little above the measuring inaccuracy of the used system.

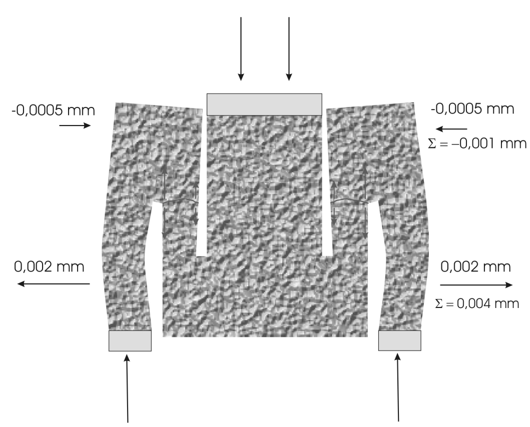


Figure 3: Scheme of the measured lateral and axial deformations of MTT sample under load. Note that lateral deformations are shown with 300x magnification.

5 RESULTS FROM THE FINITE ELEMENT STUDIES

In order to further investigate stress distribution during testing, the MTT was simulated with a non-linear finite element calculation at the Professorship for the Analysis of Civil Engineering Structures at the TU München. The sample was modeled using four-node axisymmetric 2d solid elements (Figure 4, upper right).

The material model is based upon the incremental flow theory within the framework of the theory of plasticity and was originally developed for the calculation of concrete and steel fiber reinforced concrete structures. The yield surface is composed of two partial areas, in order to be able to model different material behavior under compression and tension. Tensional failure is described by the Rankine criterion with linear, isotropic softening and a fracture energy concept. Under compression the Drucker-Prager criterion is used which shows both isotropic hardening and isotropic softening.

The qualitative results of the finite element calculation are illustrated in the upper left part of Figure 4. The diagram shows the correlation between the mean tensional stress σ_m (which is calculated from the load F and the area of the tension zone A_{TZ}) and the axial deformation u.

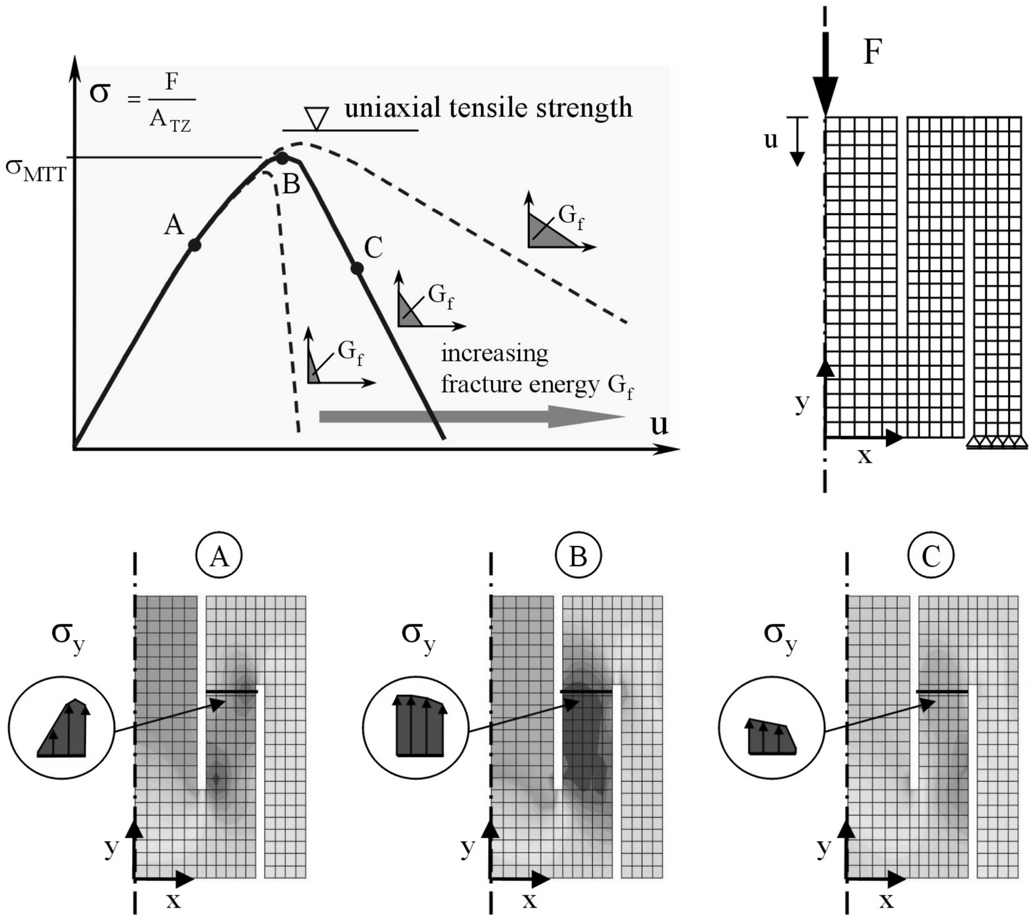


Figure 4: Models for and results from the finite element analysis.

In the lower part of Figure 4, the distribution of stresses in y-direction is illustrated in cross sections through one half of the sample for 3 different stages of the test: (A) shows the stress distribution in the pre-failure area, (B) is at maximum load (failure point) and (C) shows the post-failure situation. The calculations give rise to the supposition, that the variable stress field in the pre-failure area (A) becomes more or less equally distributed in the tension zone when the failure point is reached (B). This effect shows to be largely influenced by the ductility of the material.

The maximum mean tensile strength σ_{MTT} calculated from the finite element model is only a little lower than the implemented material tensile strength. The difference correlates to the ductility of the material which is described by the tensional fracture energy. With increasing ductility of the material, the calculated maximum mean tensile strength σ_{MTT} comes closer to the implemented material tensile strength due to a more equal stress distribution.

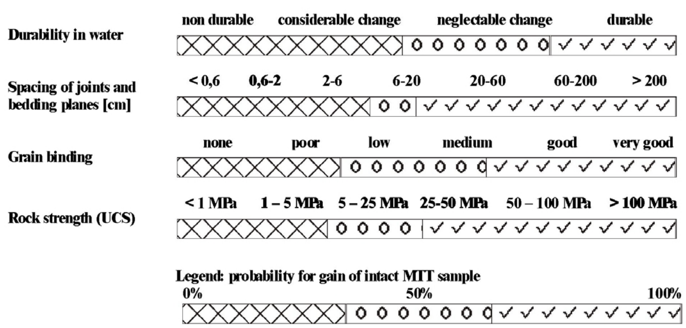
As a result of the calculations, the authors state that the tensile strength obtained in the MTT is rather equal to the theoretical uniaxial tensile strength of a material with respect to the normal variation of testing results.

6 EXPERIENCES AND SUGGESTIONS FOR MTT TESTING

6.1 *Requirements for the testing material*

Preparation of an MTT sample includes at least two different coring processes which in most cases is done using water-cooled boring machines. Consequently, jointed, weak or non-durable materials may not be suitable for testing due to a lack of stability that may lead to the destruction of the sample at the formatting stage. As a simple guide for judging whether a material is suitable for formatting, a classification system was developed by WOLSKI (2002) from his experiences on samples from bunter sandstone, lower muschelkalk limestone, phyllite, rhyolithe, granite mylonite and quartz conglomerate (Table 2). A material is suitable for preparation if all influencing factors are located in the "good" areas of Table 2.

Table 2: Criteria for material suited for MTT sample preparation.



6.2 *Preparation of MTT samples*

For the investigations on hardrock samples a water-cooled boring machine was first used with a 120 mm diameter diamond core bit to core cylinders out of blocks. Further preparation was done with a diamond rock saw and a disc grinding machine for preparation of the sample faces. The cylinder was then over cored from both ends with core bits of 79 mm and 47 mm diameter. The length-diameter ratios varied between 0.5 and 1.4.

In contrast to this preparation, the authors suggest the use of larger diameters over 200 mm for coarse grained rock samples (e.g. conglomerates, breccias, coarse grained granites) or concrete and steel fiber reinforce concrete samples. Depending on the maximum grain size of the material, such diameters are of crucial importance for a representative size of the tension zone.

At the beginning of preparation works, it turned out to be a problem to assure both core drillings being centered and vertical. This problem could be solved by using guiding construction for drilling.

6.3 *Modification of sample geometry*

Especially for investigations on steel fiber reinforced concrete, constant stress distribution in the tension zone had to be assured for the whole pre and post-failure phase of the test. This was achieved using two additional core drill holes as shown in Figure 5. Consequently, the central area of the tension zone - with constant stress distribution - was further weakened and the initial crack was forced to propagate here.

This testing setup has proved to deliver very good properties for steel fiber reinforced concrete. In combination with deformation-controlled testing and monitoring of the whole stress-strain path, it also allowed detailed and realistic investigation of the post-failure behavior, which for this type of concrete is defined by distinctive post-failure strength due to steel fibers being pulled out of the concrete matrix after failure (Figure 5).

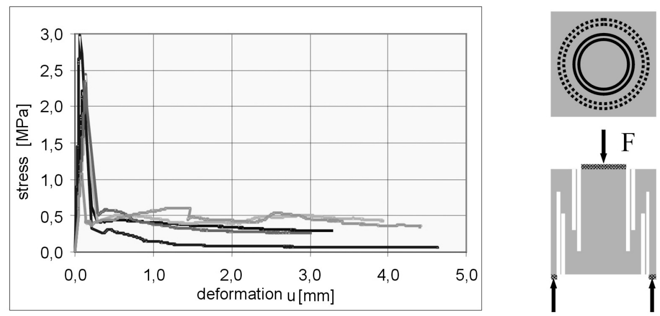


Figure 5: MTT testing results for deformation-controlled tests on steel fiber reinforced concrete samples with modified geometry. Besides the pre-failure behavior such MTT tests are able to deliver properties for the post-failure behavior of ductile materials.

6.4 *Testing setup and control*

The MTT tests were carried out following the ISRM suggestions for uniaxial compressive strength tests (ISRM, 1978b). Depending on testing material and investigation aims, the tests were either simple stress-controlled tests to the failure point with a constant loading rate of 0.05 MPa/s or deformation-controlled tests including the whole stress-strain path. Forces were applied using 5 mm V2A steel plates and rings in the size of the sample geometry.

Good experiences were also made with the testing system, a ToniNorm UCS testing machine with a testing frame for 200 kN maximum load. Sample deformation was measured using three different measuring devices: Total axial deformation was monitored via three inductive displacement transducers between the load plates. Lateral and axial deformation were measured via a device with several displacement transducers that was mounted onto the sample surface.

Logging and analysis of the collected data were done by a HBM Spider 8 data logger and a PC system with HBM CatMan 2.0 and Microsoft Excel software.

It appeared useful to conduct these tests without a ball joint at the loading plates. If an initial crack formed in one side of the tension zone, a ball joint will further propagate only this crack, which may in the worst case lead to asymmetric stress distribution and inclination of the inner core.

6.5 *Parameters from the MTT*

During all tests, total axial deformation and applied force were logged and plotted in a force deformation diagram like those shown in Figures 2 and 5. The MTT tensile strength is calculated for the failure point using Equation 1.

Calculation of deformation modules (e.g. a kind of Young´s module) from this plot does not appear useful since complicated load transfers take place in the sample during testing and thus a calculated deformation modulus would not be very significant for describing any compression or tension behavior of the material.

For significant ductile behavior (like the tested steel fiber reinforced concrete) calculation of a post-failure tensile strength is possible.

7 CONCLUSIONS

Judging from their experience, the authors evaluate the Modified Tension Tests as an innovative and easy-to-carry out testing procedure for determining the uniaxial tensile strength of hardrock and building materials. The MTT shows a good ratio for required testing equipment and demands for the testing material.

In detail, the MTT is characterized by the following positive features:

1. The tensile strength determined with the MTT comes very near to the real tensile strength of a tested material or rather equals the tensile strength with respect to the normal variation of testing results due to material differences.
2. The MTT provides good possibilities for monitoring material behavior in the post-failure area of ductile materials.
3. In comparison with standard UCS tests, the MTT needs no or only little extra expenses with regard to time, costs and required equipment.
4. The MTT is very well suited for materials with high strength (especially hardrock), where the use of adhesives is no longer possible.

8 REFERENCES

BLÜMEL, M. (2000):Neue Laborversuchstechniken für felsmechanische Versuche (Improved Procedures for Laboratory Rock testing).- DGGT (ed.): Proceedings of the EUROCK 2000 Symposium, Aachen, 27.-31. März 2000: 573-578, Essen (Glückauf)

DGEG - Deutsche Gesellschaft für Erd- und Grundbau e.V. (1982): Empfehlung Nr. 5 des Arbeitskreises 19 Versuchstechnik Fels der DGEG: Punktlastversuche an Gesteinsproben.- Bautechnik, 1982, 1: 13-15, Berlin (Ernst)

DGEG - Deutsche Gesellschaft für Erd- und Grundbau e.V. (1985): Empfehlung Nr. 10 des Arbeitskreises 19 Versuchstechnik Fels der DGEG: Indirekter Zugversuch an Gesteinsproben – Spaltzugversuch.- Bautechnik, 1985, 6: 197-199, Berlin (Ernst)

DIN - DEUTSCHES INSTITUT FÜR NORMUNG (1991): DIN 1048, Teil 5: Prüfverfahren für Beton. Festbeton, gesondert hergestellte Probenkörper.- 8 p. Berlin (Beuth)

FECKER, E. & REIK, G. (1996): Baugeologie.- 429 p., Stuttgart (Enke).

ISRM-INTERNATIONAL SOCIETY FOR ROCK MECHANICS (1978): Suggested methods for determining tensile strength of rock materials. Commission on Standardization of Laboratory and Field Tests.- International Journal of Rock Mechanics, Mining Sciences and Geomechanical Abstracts, 15: 99-103.

ISRM-INTERNATIONAL SOCIETY FOR ROCK MECHANICS (1978b): Suggested methods for determining the uniaxial compressive strength and deformability of rock materials. Commission on Standardization of Laboratory and Field Tests.- International Journal of Rock Mechanics, Mining Sciences and Geomechanical Abstracts, 16: 135-140.

ISRM-INTERNATIONAL SOCIETY FOR ROCK MECHANICS (1985): Suggested method for determining point load strength. Commission on Testing Methods, Working Group on Revision of the Point Load Test method.- International Journal of Rock Mechanics, Mining Sciences and Geomechanical Abstracts, 22: 51-60.

PRINZ, H. (1997): Abriß der Ingenieurgeologie.- 546 p., Stuttgart (Enke)

THOMÉE, B. (in preparation): Strukturmechanische Modellierung von Stahlfaserbeton (working title).- PhD-thesis TU München

WOLSKI, K. (2002): Der Modified Tension Test – Aussagekraft und Durchführbarkeit eines neuen Zugversuches.- Diplomarbeit am Lehrstuhl für Allgemeine, Angewandte und Ingenieur-Geologie der TU München.- 52 p. (unpublished).