EVALUATION OF A TENSILE TEST FOR THE DETERMINATION OF THE MATERIAL BEHAVIOUR OF FILAMENT YARNS UNDER HIGH STRAIN RATES

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Abstract:

In many technical applications, fibre-reinforced composites with textile high-performance fibres made of carbon or glass are being used. The fibres qualify for their high strength and stiffness due to their physical and chemical characteristics. It is necessary to guarantee a high safety level under all possible loading constellations. Besides the usual service loads, the topic of extreme loads that work along with high forces and high impact velocity is of increasing importance. For these so-called impact loads, the processes within the structural components have to be analysed and material models suitable for prognoses should be derived from them. The existence of suitable test machines and test methods is a prerequisite for that, yet for filament yarns they are not state of the art. Hence, tensile tests with high strain rates on filament yarns are performed on standard high-speed tensile testing machines. This leads to problems when analysing and interpreting the results and therefore, it is necessary to develop special testing machines for filament yarns.

Key words:

Fibre reinforced concrete, impact load, high impact velocity, high strain rates, high speed tensile tests, high performance yarns

Introduction

In the field of composite material, the topic of impact loads has been gaining more and more importance due to increasingly complex constructions and the constantly increasing safety demands. One current topic is energy-intensive loads that occur suddenly and only temporarily, as in impact or explosions. In this context, high tensile forces develop in the textile reinforcements which are embedded in the composite during impact times of micro- or milliseconds. Accordingly, the textiles have to absorb high strain rates and therefore need a high energy absorption potential when deformed. In this case the material behaviour does not correspond to the known behaviour under static and quasi static loads. The development of suitable calculation and measuring models under such impact loads demands a detailed analysis of the processes occurring in the material and an exact knowledge about the failure mechanisms of the textile structures responsible for the transfer of the tensile forces.

The focus of the present study is the evaluation of the currently available test stands and measuring methods which help research the stress-strain behaviour of multifilament yarns under high strain rates.

Initial situation and aim

The subject of the material behaviour of textile fabrics under high strain rates plays an important role when focusing on main points such as impact-exposed applications in the field of fibre-reinforced polymers. Many researches already exist which deal with the topic of the behaviour of composite material with regard to the modelling of the damage and the prognosis of the remaining load-bearing capacity. Especially in the field of vehicle construction and aerospace technology, impact processes are significant for the evaluation of crash behaviour [3, 12]. Another application field is the use of high-performance textiles in bullet-proof vests and helmets which are especially designed for impact loads [2, 15]. Researches concerned with that show that the deformation and failure behaviour of textile fibre-reinforced structures under high load rates can only be presented realistically when enough knowledge is present about the load condition occuring in the process and the energy absorption potential of all materials in the compound. Moreover, possible delamination effects between the textile fibres and the surrounding matrix need to be considered.

Buildings and other massive constructions can be exposed to local impact loads when under extreme external impacts. With respect to that, former researches mainly analyse the behaviour of the concrete or the brickwork under impact-related influences [19, 20]. Building upon that, a modelling of the supporting structure under highly dynamic loads can be realized with the help of the finite element method [8, 25].

A rather new technology is the application of textile structures as a reinforcement in concrete components either as an alternative to the standard steel reinforcement or in the course of the renovation and reinforcement of existing constructions. In this field, extensive research has been carried out and by now, sufficient knowledge about the behaviour under mainly constant loads is available [4, 7, 10].

With an increasing application as well as a look into possible extreme impact effects such as explosion or aircraft crash on the buildings, the necessity for the evaluation of impact behaviour is being given more priority. Already for a long time, Ultra High Performance Concrete (UHPC) with very high compressive strength has been worked on, which is successfully used in the security-related areas of massive buildings (e.g. nuclear reactors) [27]. To improve the tensile strength and to restrict cracking, textile fibres are added, yet at the moment preferably short fibres. With this, a significantly more ductile material behaviour can be realized and therefore, possible damage can be reduced.
The description and the modelling of the processes taking place under impact load in components or buildings require extensive knowledge about the strain-rate dependent strength, not only for the composite material as a whole but especially also for the applied textile structures. For this, tests are used in which the yarn is rapidly broken with extremely high loading rates. The testing methods applied for this problem range from high speed testing machines via rotation test stands, drop- and pendulum impact testing machines to test stands powered by explosions, see examples in Figure 1. In all cases, the stress-strain behaviour of the tested specimen has to be recorded as precisely as possible within an extremely short test duration of usually less than one millisecond which, therefore, demands high frequency measuring methods. Two of the leading providers of such test machines are the companies Zwick GmbH & Co. KG (Ulm, Germany) and Instron (Norwood, USA). Furthermore, a variety of special test machines exist for special measurements in research facilities and companies. However, there are no standardized and established testing methods or machines for short-term dynamic tensile test of textile multifilament yarns. Therefore, the testing machines developed mainly for metallic test specimens need to be evaluated and adapted for their suitability. In a second step, suitable methods for the precise measurement of the load-time curve and the path-time curve need to be developed and applied.

**Research status**

Former research on impact-loaded high-performance fibres are primarily connected to the applications in fibre-reinforced polymers: the analysis of filament yarns alone is rare. This can be ascribed to the fact that the research of the strain behaviour of high performance filament yarns with a sufficiently high measurement accuracy is only possible when performed and evaluated carefully even under quasi-static load. Significant problems can be found in the clamping technique and in the determination of the length change. Test machines optimized to answer such questions are not available to everybody. Basically, it can be stated that the according material characteristics are not derivable from the common knowledge under quasi static load. Available literature about the testing of reinforced and non-reinforced synthetic materials allows conclusions on the testing method and the behaviour of the test machine during the test besides the evaluation of the material properties.

Research for the determination of the parameters which are dependent on the strain rate, such as failure, as well as the damage behaviour of composite components made of glass fibre multi-layer weft knits (GF-MLG) show that increasing strain rates correlate to the increase of tensile strength, strain and stiffness [11]. A servohydraulic high performance test unit by Instron was used for the test in combination with a laser doppler extensometer and a high speed camera. The test probes were analysed under strain rates of up to 40 s\(^{-1}\). With an increasing loading rate, oscillations occur that result from the stimulation of the natural frequency of the entire test system and which overlay the measuring results.

Similar results could be achieved for short glass-fibre reinforced polyolefins with a servohydraulic test machine VHS 25/25-20 by Instron. With a test length of 115 mm, strain rates of up to 174 s\(^{-1}\) could be reached. A positive strain-rate related behaviour was found for the analysed material. When strain rates are higher, the stiffness increases while the strain decreases at the same time. When the strain rate is higher than 20 s\(^{-1}\), this effect is much more pronounced which can be referred to the transition from isothermic to adiabatic behaviour. This measurement process also possesses obvious oscillations of the measuring system with increasing strain rates. A clear increase of the tensile strength with carbon fibre-reinforced polymer can be observed with an increasing strain rate [9]. Yet, a direct connection between Young’s modulus and the strain rate could not be found in the probes tested. The behaviour of polymers under highly dynamic loads has also been analysed in numerous research papers. It resembles that of fibre composites and shows a higher tensile strength while the strain decreases at the same time when strain rates increase [6, 17, 29].

Further research deals with the material behaviour of composites with respect to the modelling and the prognosis of the remaining load-bearing capacity after impact [13]. Here, the results show that the deformation and failure behaviour of fibre-reinforced composites under highly dynamic load can only be realistically understood if there is sufficient knowledge about the process taking place in the material [3]. To determine and model material properties dependent on strain rates, there are first basic approaches [2, 23]. For example, a modified G’Sell-Jonas-Modell for the calculation of material characteristic values with high strain rates was applied in [23]. The according strains with a maximum tension from the quasi static tensile test were used as initial points. With that, it is possible to describe the strength properties which are dependent on the strain rates. For test speeds of more than 20 m/s, test methods are currently not available, and the existing tests are not suitable, without any adjustment, for the analysis of high-performance fibres. Moreover, material models for such high load speeds do not exist.

With regard to the application of metallic or polymer reinforcements for concrete components, there is not yet sufficient knowledge about the behaviour of fibre materials under impact load. The research that has been performed in this field so far mainly deals with the behaviour of pure concrete under highly dynamic load. Thus, it has been known for a longer period of time from the technical literature that the increase of the strain rate leads to an increase of the tensile strength [1, 5, 16, 18, 21, 22, 28]. Also, the effect of fibre reinforcement increasing in stiffness leads to a restriction of crack formation.
and to a ductile material behaviour, as proved in numerous tests [26]. First research on the behaviour of 2D or 3D textile reinforcements for concrete components under explosion load shows an evenly improved behaviour compared to standard steel reinforcements [14]. In studies of sisal-reinforced concrete test bodies, the positive effect of the textile reinforcements under impact load in the form of wider crack openings could be proved [24].

High speed tensile tests on filament yarns

Based on extensive experience in the field of textile testing under static and quasi static loads, first own tensile tests were performed with the yarns listed in Table 1 on the servohydraulic high speed testing machine presented in Figure 1a. The operating principle of this test machine by Zwick is representative for the currently used industry standard. The object of these tests was the development and testing of suitable sample holders as well as the identification and judgement of significant issues for force and distance measuring. First knowledge about the stress-strain characteristics of multifilament yarns loaded dynamically in a very short time period was gained and significant parameters for the measured values to be specified were worked out. With this, an important foundation was laid for the approach in further research activities.

Table 1. Test program for tension tests under high strain rates.

<table>
<thead>
<tr>
<th>Tested yarns</th>
<th>Yarn count</th>
<th>Test speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon filament yarn, uncoated</td>
<td>800 tex</td>
<td>1 m/s, 2 m/s, 5 m/s, 10 m/s, 15 m/s, 20 m/s</td>
</tr>
<tr>
<td>AR-glass filament yarn, uncoated</td>
<td>640 tex</td>
<td>20 m/s</td>
</tr>
<tr>
<td>Aramid yarn</td>
<td>336 tex</td>
<td>20 m/s</td>
</tr>
<tr>
<td>Polyethylene (Dyneema)</td>
<td>175 tex</td>
<td>20 m/s</td>
</tr>
<tr>
<td>Steel filament yarn</td>
<td>500 tex</td>
<td>20 m/s</td>
</tr>
<tr>
<td>Steel wire Ø 0.6 mm</td>
<td>complies with 2220 tex</td>
<td>20 m/s</td>
</tr>
</tbody>
</table>

Figure 2 shows a test on a carbon filament yarn. The massive connection points in the test machine, which are designed principally for metallic test bodies and much higher tensions, can be seen very clearly. The high speed camera in the background records both changes in path length as well as the breaking process of the yarn probe during the tension test, which lasts only fractions of a millisecond.

Test set-up and performance

The aim of the high speed tension tests on textile yarns is to research failure mechanisms at very high strain rates widely unknown up to today. Here, the relative change in length within a (very short) time frame is observed and therefore, the shortest possible length of the test body in the test set-up should be striven for. In Figure 3, the dependence of the strain rate on the length of the test body is presented, as can be expected for small strain rates from the knowledge about static and quasi static conditions. With this, an inversely proportional context exists which means doubling the length of the test body results in half the strain rate and the latter decreases analogously to the test speed starting at the load feeding point to the clamping end of the test body linear down to zero. In the middle of the test body, the strain rate is therefore half of the maximum strain rate max at the load feeding point.

Figure 2. High speed tension test on a carbon filament yarn 800 tex with a testing speed of 20 m/s (left: before the test; right: after the test)

Figure 3. Connection between test body length, test speed and strain rate.

The smallest test body length possible between the clamping devices is mainly determined by the given conditions in the test machine and the necessary space requirement for measuring the change in length during the test. There were free test lengths of about 10 to 15 cm in the tension tests performed on textile high performance fibre yarns and with the available technical equipment. In Figure 4a one can see the clamping device for the test screening that was used in the first tests, which had been developed for that purpose. It allows a slip- and damage-free clamping of the multifilament yarns under those high strain rates. Their adaptation within the test machine is schematically presented in Figure 4b.

Figure 4. Clamping of the textile yarn probes in the high speed tension testing machine:

a) Test holder developed for the clamping of multifilament yarns,

b) Schematic sketch.

One focal point of tension tests performed with this test set-up is the study of carbon filament yarns with a yarn count of 800 tex, as used in many technical applications. For those, the characteristics presented in Table 2 can be applied with a maximum possible test speed of 20 m/s. However, an exact determination is not possible with the currently available technical equipment.
As can clearly be seen, this method is not adequate for determining yarn tensions under the required test speeds. The application's limitation is, in this case, to measuring frequencies of 6 to 7 kHz, which means the release of measured values is about 0.15 ms. Test speeds of up to 1 m/s can be covered quite reliably with the tested carbon filament yarns having the marginal conditions presented in Table 2. In the course of future research, load measuring devices with clearly higher natural frequencies need to be developed for the determination of load-time courses with higher speeds. A significant aspect in this is the mass of the entire system made of the load transducer and the connected clamping device. These components work together according to the principle of a spring damper system and they are subject to more or less heavily distinct self-oscillations according to their mass and stiffness distribution when stimulated by a load impulse (impact of the load). Hence, they need to be constructed with a low mass and a high stiffness at the same time for the measurements to be performed.

### Collection of data during the tension test

The test period which is listed among the conditions in Table 2 and which means the time frame between the impact of the load and the actual breaking is theoretically only 0.05 ms. During this time period, the yarn tension and the change of the length have to be determined. This demands the use of high frequency measuring methods to be able to collect enough measuring values for meaningful results. Based on this, the stress-strain characteristic of each yarn can be determined from the entering force until the breaking and the resulting stress-strain characteristic of each yarn can be determined in the theoretical measuring period of 0.05 ms. Since this sampling frequency is clearly above the natural frequencies of 6 to 7 kHz, which means the release of measured values is about 0.15 ms, Test speeds of up to 1 m/s can be covered quite reliably with the tested carbon filament yarns having the marginal conditions presented in Table 2. In the course of future research, load measuring devices with clearly higher natural frequencies need to be developed for the determination of load-time courses with higher speeds. A significant aspect in this is the mass of the entire system made of the load transducer and the connected clamping device. These components work together according to the principle of a spring damper system and they are subject to more or less heavily distinct self-oscillations according to their mass and stiffness distribution when stimulated by a load impulse (impact of the load). Hence, they need to be constructed with a low mass and a high stiffness at the same time for the measurements to be performed.

### Realization of the load measurement

For the determination of the yarn tension with the high speed test machine presented in Figure 1b, a load cell integrated in the test machine is used in the pretests. This cell is built into the bottom part of the testing machine, which means in the fixed clamping end, and it is used for the measurement of forces of up to 50 kN. The load cell is based on the Piezo technology and has a weight of about 250 g and a natural frequency of about 10 kHz according to the manufacturer’s information. As long as measuring and sampling frequencies are clearly below that natural frequency, precise statements can be given about the applied forces. The load cell was triggered with a sampling frequency of 125 kHz during the performed tests. With this, 6 measuring values can be collected in the theoretical measuring period of 0.05 ms. Since this sampling frequency is clearly above the natural frequency, a measurement of the yarn tension is not possible. The values presented by the load cell instead show an oscillation curve which is caused by the spring damper system created by the load cell with both overall masses and the subsequent test clamping and the resulting natural frequency at the moment of the impact of the load impulse. Two of the typical processes for such load measurements are presented in Figure 5 for different test bodies.

### Table 2. Theoretical characteristics of the high speed tension tests for carbon filament yarns 800 tex at a traverse speed in the test machine of 20 m/s.

<table>
<thead>
<tr>
<th>Test body / Roving</th>
<th>Carbon filament yarn 800 tex</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross-section of the roving</td>
<td>$A_t = 0.447 \text{mm}^2$</td>
</tr>
<tr>
<td>Length of the test body between the test holders</td>
<td>$L_o = 120 \text{mm}$</td>
</tr>
<tr>
<td>Speed of the load feeding</td>
<td>$v_o = 20 \text{m/s}$</td>
</tr>
<tr>
<td>Breaking strength</td>
<td>$F_{br} = \sim 1 \text{kN}$</td>
</tr>
<tr>
<td>Increase of length till failure</td>
<td>$\Delta l_o = \sim 1 \text{mm}$</td>
</tr>
<tr>
<td>Breaking strain</td>
<td>$\varepsilon_{br} = \sim 8 %_o$</td>
</tr>
<tr>
<td>Test period until breaking</td>
<td>$t_{br} = 0.05 \text{ms}$</td>
</tr>
<tr>
<td>Maximum strain rate at the top clamping end</td>
<td>$\dot{\varepsilon}_{max} = 160 \text{ s}^{-1}$</td>
</tr>
<tr>
<td>Average strain rate in the middle of the test body</td>
<td>$\dot{\varepsilon}_{av} = 80 \text{ s}^{-1}$</td>
</tr>
</tbody>
</table>

As can clearly be seen, this method is not adequate for determining yarn tensions under the required test speeds. The application’s limitation is, in this case, to measuring frequencies of 6 to 7 kHz, which means the release of measured values is about 0.15 ms. Test speeds of up to 1 m/s can be covered quite reliably with the tested carbon filament yarns having the marginal conditions presented in Table 2. In the course of future research, load measuring devices with clearly higher natural frequencies need to be developed for the determination of load-time courses with higher speeds. A significant aspect in this is the mass of the entire system made of the load transducer and the connected clamping device. These components work together according to the principle of a spring damper system and they are subject to more or less heavily distinct self-oscillations according to their mass and stiffness distribution when stimulated by a load impulse (impact of the load). Hence, they need to be constructed with a low mass and a high stiffness at the same time for the measurements to be performed.

### Realization of the displacement measurement

A high speed image acquisition system consisting of a high speed camera and the evaluation software is used for the displacement measurement. The basic set-up and functionality are presented in Figure 6. The photographic recording of the test body with two applied measuring marks is done with a recording frequency of 125 kHz. With optoelectronic methods, the path-time courses can be determined in the first step and after the differentiation, the length increase of the test body can be determined in the
second step. The evaluation provides the overall value of the yarn strain as a function over time based on the initial length. Furthermore, the used system allows the observation of any number of measuring values with the help of the test body length. With this, it will be possible in further research to not only determine the overall strain but also to make statements about the course of the strains using the yarn length.

Results and evaluation

The performed high speed tension tests allow first conclusions about the deformation behaviour of the tested yarns under the applied test conditions. For this, the path-time courses recorded with the high speed image acquisition system are being analysed more closely. The measuring point fixed on the top end of the yarn represents the deformation course of the stretched yarn as well as the movement of the top yarn holding and therefore, the movement of the securely fastened (in the sense of infinitely stiff) piston rod in the test machine. After the derivation of the time, the approximate speed can be determined at the measuring point from the path-time curve. This is presented in the following using an exemplary test of a carbon filament yarn 800 tex. Figure 7a shows their path of motion which means the path of motion of the end test set-up in the test machine which is to be accelerated. As can clearly be seen, the curve starts with a very flat increase which becomes steeper in the course of the experiment. In Figure 7b, the course of the speed gradient determined from this data is shown. This is also not linear and there is a continuous increase of speed up to the peak of, in this case, 20 m/s.

Important conclusions which can be dealt with in future research can be drawn from the described observations of the performed tests. Those significant aspects are summarized in the following.

Acceleration process in the testing machine

The used high speed testing machine Zwick HTM works on a servohydraulic base in whose work cylinder a piston is accelerated to the target speed. This can happen in both directions which means for both pressure and tension tests. A carrier is closely connected to the piston which provides the necessary start-up length for the acceleration to the target speed. At the end of the start-up length, the carrier connects to another piston on which the load feeding into the top clamping end of the test body occurs. The contact area between the carrier and the piston rod is disguised with elastic material to minimize wearout. With this - as well as due to the inertia of the piston rod itself - a finite time period \( \Delta t \) and an associated path \( \Delta l \) is always necessary until the piston rod has reached the speed of the carrier as well. The acceleration process happening thereby is dependent on the mass and stiffness relations of all participating components and can only be partly influenced when a standard test machine is used. A closer analysis of the processes taking place in the test machine at the moment of the acceleration process is therefore necessary for the evaluation of the test results.

Load feeding speed at the impact on the test specimen

When the testing machine equipment and a secure connection with the top clamping end of the specimen is used, a load feeding with the rated speed can inevitably not take place, but the identical acceleration process described above is performed here. To reach an impact of the load on the specimen with a maximum speed, a further start-up length was necessary between the piston rod of the test machine and the top specimen holder that has to cover their speed path \( \Delta l \) (about 1 to 2 mm). The following requirements should be made for the transmission of the load impulse in the test body:

- Acceleration of the specimen holder from zero to target speed \( \rightarrow \infty \).
- Mass of the specimen holder (if necessary including force measuring element) \( \rightarrow 0 \).
- Stiffness of the specimen holder \( \rightarrow \infty \).

Since there are physical limitations to the requirements described above, the achievable speeds in the test body will
**Conclusion**

With the tests performed, it was possible to gain first important knowledge for future tension tests of textile yarns under high load rates. Significant aspects of the test set-up as well as the necessary measuring methods for the determination of the load-time course and the path-time course within a very short test period could be identified. Numerous changes have to be done on textile test bodies for tensile tests of yarns as is foreseeable from the collected experiences on the high speed test machine of the company Zwick. This mainly includes the clamping of the yarns, the problem of the transmission chain of the load impulse starting at the servohydraulic working cylinder via the start-up length and the contact to the following piston rod and to the test body as well as the adjustment of the carrier to meet the demands regarding measurements under very high load rates.

Especially the problem of force measurement under high test speeds in combination with a suitable test stand will be the focus of future research. The main task here is the realization and optimization of a test stand that reaches a high resonance frequency of the entire force measuring device even with a minimized weight and very high stiffness of the moved components. Only so can oscillation influences be reduced and enough meaningful measured values be recorded in the extremely short test time of clearly under one millisecond.

Furthermore, it could be noticed during the performed tests that the semi-elastic damping during the power transfer from the test machine to the test body with the help of an accelerating piston causes a long delay in the target speed’s being reached. Hence, technologies need to be developed that help the load initiating device coming from the test stand to push the test body to reach the target speed within the shortest time possible. To keep the forces which would accompany this as low as possible, the constructional details such as the clamping of the test body and the integration of the force measuring devices have to be optimized further. Falling weight test stands as well as centrifugal ones, for example, are suitable for the realization of these requirements, in which a carrier transfers the force impulse striking the test body almost without delay and with a constant target speed as well as a high mechanical energy. These aspects are the focal points of our current and future research.

Regarding the deformation measurement, good results have been achieved so far using high-speed image acquisition systems. However, experience has shown that the technology of optoelectronic evaluation on filament yarns is very difficult to use since those yarns do not provide connected, self-contained areas along the length of the test body. For a qualitatively reliable and reproducible evaluation of the measured deformations, a further need for research and optimization exists here as well. This enquiry into the research status of the field of material testing under impact load has shown that due to the stringent demands of yarn testing, test stands solely and especially constructed for that purpose are often employed. In current works, the possibilities of special test set-ups with integrated load and path measurement methods are examined and first prototypes are practically implemented in the frame of pretests based on the defined requirements on the tensile test of textile high performance fibre yarns. The force measurement is performed on both the fixed and the accelerating clamping end.

Figure 7. Presentation of an exemplary motion course of the measuring point fixed upon the speed up end for a carbon filament yarn 800 tex (complies with the motion sequence of the piston rod in the test machine):
- a) presentation of all measured path-time courses,
- b) presentation of the calculated speed-time course.

always be dependent on the chosen test set-up. It is a main task for further research to optimize this set-up.

Realization of the load and displacement measurement

As all performed tensile tests have clearly shown, it is basically not possible to determine the forces in the test body for speeds of more than 1 m/s with the test machine’s internal Piezo-carrier due to its relatively low natural frequency. The application of a load measuring element with a significantly lower mass and higher stiffness whose natural frequency has to be clearly above the necessary measuring frequency is required for high frequency force measurements. For this, Piezo-carriers with the corresponding technical characteristics are preferable. Alternatively, an indirect load measurement using strain gauges which are fixed on a carrier integrated in the clamping device is also possible as long as it has a sufficiently high natural frequency.

Besides the problem of the force measurement, there is a second challenge in the performance of the high frequency path measurement. Here, first tests have shown that a very precise determination of the motion processes of the measuring marks fixed on the test body is possible with optoelectronic methods when a high speed camera is used. The evaluation of these motion processes will not only provide detailed information on the absolute length change but also on the strain course with the help of the yarn length. This technology will therefore have to be analysed further in future research.
In conclusion, it can be determined that the main task of research dealing with the load-deformation behaviour under impact loads consists to a substantial degree of the control of the measuring methods for force and path within the extremely short test period. This is valid for textile yarns and also for all other materials under this load scenario.

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