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Microcracking in dog bone under load

A biomechanical study of bone visco-elasticity

Entire diaphyseal bones from adult dogs were repeatedly loaded in torsion. The residual deformation after unloading from the non-linear deformation range was found to decrease with time. Acoustic-emission signals typical for micro-cracking were registered not only during loading in the non-linear deformation range but also during the initial phase of the following unloading. The initial torque and twist required for further micro-cracking decreased for every subsequent load-cycle, i.e. with the amount of cracking already formed. These observations are indications of visco-elastic properties of bone material.

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When an entire diaphyseal bone is twisted, the deformation is initially linear and elastic. At a certain twist the deformation becomes non-linear. Many investigators (Chamay 1970, Piekarski 1970, Burstein et al. 1972, Pope & Outwater 1972) have associated the non-linear properties of bone with plastic deformation. This means that a bone should be permanently deformed after loading into the non-linear range. Netz and co-workers have, however, shown (1980b) that entire diaphyseal bones from adult dogs are essentially elastic-brittle. The non-linear deformation is caused by a gradual formation and/or growth of micro-cracks, which decrease the stiffness of the bone (Netz et al. 1979, 1980a).

Crack propagation in cortical bone material has been studied previously. Pope & Outwater (1972) studied the effect of pre-cracking of the bone and Carter & Hayes (1977) the significance of micro-cracks for fatigue damage of machined cortical specimens. In order to study the significance of micro-cracking for ultimate fracture of diaphyseal bone, it is necessary to use entire and intact bones.

The aim of the present study was to elucidate further the properties of the non-linear deformation of long bones, especially the significance of micro-cracking for the initiation of ultimate fracture and the nature of the residual deformation.

Material and methods

The test material consisted of fresh, related pairs of tibiae and of femora from healthy, adult mongrel dogs of both sexes.

Preparation

After the animals had been sacrificed with a lethal dose of Pentothal-Natrium® (Abbott Laboratories, Italy) administered i.v., the bones were taken out and all soft tissues including the periosteum were removed. The bones were kept in saline-soaked gauze at 19–22°C. All bone pairs from the same series were treated identically.

Equipment

A previously described torsional test method, originally developed by Strömberg & Dalén in 1976, has been modified and connected to a micro-computer to control and record repeated loadings of entire long bones. The delay at zero load between two load-cycles can be varied, and the residual deformation at the start of the subsequent load cycle is registered.

Stress-waves produced in solids as a result of application of loads are conveniently studied with the acoustic emission technique (A.E.). The A.E. equipment and method described by Netz et al. (1980a) for testing of bones have been modified. Stress waves in the bone surface are transmitted by a pinpoint wave-guide to a piezo-electric transducer. After amplification and processing, the signals are recorded by a sensitive ultra-beam recorder, The corresponding torque and twist signals are simultaneously fed to the recorder and to the computer.

The characteristics of acoustic emission signals (amplitude, frequency and distribution) vary according to the material tested and the emitting source mechanism (Tetelman 1971).

The A.E. signal characteristics were interpreted by technicians with much experience in the field (AB TRC, Stockholm, Sweden).

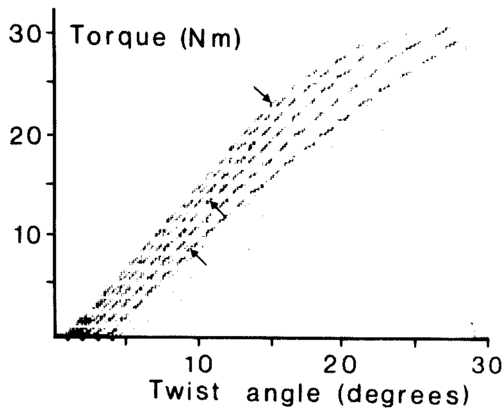

Figure 2. The right tibia of the same dog as in Figure 1 is repeatedly loaded and unloaded with a stepwise twist increase. The stiffness of the torque-twist curves decreases for every new load-cycle. Arrows indicate end of linear deformation for the first, fourth and last load-cycle.

Testing procedure

The metaphyses of the bones were fixed in two cylinders with a special metal alloy, using a technique described previously (Strömberg & Dalén 1976). All the bones were twisted inwardly and the twist rate was 6 degrees per second.

Two types of test were made:

Seven pairs of tibiae. One of the bones of each pair was twisted to ultimate fracture in one load cycle. The torque-twist curve of each bone was registered (Figure 1). The other bone of the pair was twisted just beyond (<1 degree twist) the linear part of its torque-twist curve and then unloaded by reversing the twist. After a delay of 60 s the twist was restarted and when the maximum twist of the previous load-cycle was exceeded by 2 degrees the bone was unloaded. This procedure with 2 degrees increase of twist in every load-cycle was repeated until ultimate fracture occurred (Figure 2). The torque-twist curve of all load-cycles was recorded and the A.E. activity in the bones registered.

Six pairs of femora. The bones were twisted to a point on the non-linear part of the torque-twist curve which was 0.8 Nm less than the extension of the linear part of the curve, and then unloaded (Figure 3). One of the bones was kept at zero load for 0.6 s and the other for 10 min before starting the next load-cycle. The torsion direction was reversed after a twist increase of 2 degrees compared to the previous load-cycle (Figure 2). This procedure was repeated

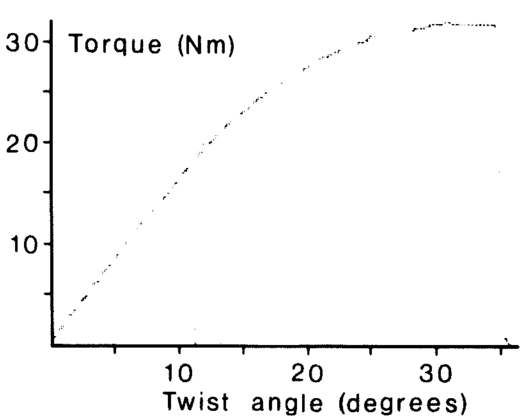

Figure 1. A torque-twist curve for the left tibia from an adult dog. The curve has been obtained by means of computerized test equipment. The linear deformation ends in this case at a twist of 11.25 degrees.

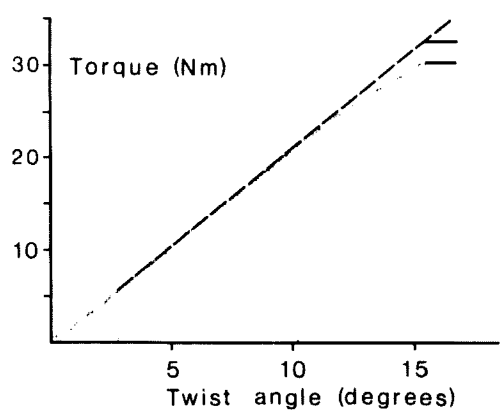

Figure 3. The amount of non-linear deviation from the extension of the linear part of the curve can be used as a criterion for the first reversal during load-unload tests.

until final fracture of the bone occurred. The residual twist at the start of the fracture load-cycle was registered.

Results

For all tibiae twisted repeatedly, ultimate fracture occurred at a smaller torque and a smaller twist compared to the paired bone twisted directly to final fracture (Table 1). The stiffness of the bones decreased for every subsequent load-cycle. The linear part of the torque-twist curves was always smaller for the fracture load-cycle than for the initial load-cycle.

Acoustic emission signals with amplitudes typical for cracking were registered during loading in the non-linear range for 10 of the 14 tested bones. For four of the seven repeatedly loaded tibiae, signals with amplitudes typical for cracking were also recorded during the initial part of one or more of the unloadings of the load-cycles.

The residual deformation after a complete load-unload cycle was significantly less for the bones kept at zero-load for 10 min compared to the paired bone with zero-load for 0.6 s (Table 2).

Discussion

Some studies of the mechanics of bone material can be performed with machined specimens (Sedlin & Hirsch 1966, Romanus 1974). When studying the fracture process of diaphyseal bone, entire and intact bones must be used. This is mainly due to the fact that bone material is anisotropic and inhomogeneous (Enlow 1966) and that the geometry of a diaphyseal bone is complex. A disadvantage of using entire bones is the lack of identical specimens. The difference between torque-twist curve parameters for entire right and left paired bones from dogs is, however, insignificant (Netz et al. 1978).

Micro-cracking has been shown to occur in the diaphyseal bone during torsion within the non-linear deformation range (Netz et al. 1980a). In this range the torque required for further cracking increases with twist. Microcracks that form at some torque are thus arrested at a slightly greater torque. In a perfectly elastic-brittle material the first crack formed should lead to ultimate failure of the bone because the stress intensity around a crack tip increases with torque and crack length. If micro-cracks are initiated in brittle regions of the bone, there must be other, tougher regions to arrest them. In fact, a large number of cracks are formed within the non-linear range of the torque-twist curve before final fracture of the bone (Netz et al. 1980a). Micro-cracks are effective local stress raisers, as pointed out by Currey (1962) and by Piekar-

Table 1. Torque and twist at final fracture of paired tibiae. One tibia of a related pair is twisted to ultimate failure in one load cycle and the other is repeatedly twisted to ultimate failure

Bone pair no.	Maximum torque (Nm)		Twist at fracture (degrees of twist)	
	One load cycle	Repeatedly loaded	One load cycle	Repeatedly loaded
1	23.5	22.1	27.8	23.3
2	25.3	21.7	38.0	23.3
3	29.9	28.0	37.8	32.5
4	32.2	30.9	35.0	29.5
5	29.1	25.0	32.5	18.8
6	27.1	25.9	33.5	29.0
7	20.4	19.1	25.8	24.3

Maximum load and deformation at fracture are greater for the tibiae twisted directly to final fracture (paired t-test; $p < 0.05$).

Table 2. Total and mean value of residual deformation (degrees of twist) of repeatedly twisted femora. Delay at zero load is 0.6 s for one of the paired bones and 10 min for the other

Bone pair no.	0.6 s delay		10 min delay	
	Total	Per load-cycle	Total	Per load-cycle
1	1.56	0.39	0.47	0.24
2	1.16	0.29	0.76	0.19
3	1.86	0.47	1.29	0.26
4	3.58	0.72	0.89	0.23
5	1.36	0.34	0.48	0.16
6	2.88	0.48	1.45	0.29
Mean:	2.07	0.45	0.89	0.23

The smaller residual deformation after 10 min at zero load compared to 0.6 s is statistically significant (paired t-test; $p < 0.05$).

ski (1970). It is logical to assume that final fracture ensues through micro-crack coalescence, when the stress intensity has been increased by the torque so that the tougher regions yield. Crack propagation is thus more difficult than initiation, implying that the bone material toughness is inhomogeneous.

Movements of the A.E. transducer at reversals during repeated loadings were avoided by using a pinpoint waveguide. This decreased the contact area. Acoustic emission signals typical for micro-cracking were not registered for all the bones. The A.E. activity was found to decrease with increasing distance between the transducer and the final fracture path. This is most probably due to a severe damping of the sound (Christensen et al. 1978), especially in the direction perpendicular to the long axis of the bone, (preparatory tests by Netz et al. 1980a) and to a non-uniform crack distribution.

A.E. signals of the burst type, which are considered typical for cracking, were observed in the non-linear deformation range. The emission rate was increasing during loading. During initial unloading the A.E. signals were also of the burst type and with the same amplitude as during loading. As the signal characteristics during unloading cannot be distinguished from those observed during loading, it follows that cracking should also occur during unloading in the non-linear deformation range.

Micro-cracking during unloading can occur through growth of previously formed cracks and/or formation of new cracks. Crack-growth during unloading must be due to a time-dependent crack-growth resistance, which decreases with time, and/or an increase of the stress intensity around crack tips through local stress redistribution. Both these effects require visco-elastic material properties.

As already mentioned, the torque required for further cracking increases with twist within a given load-cycle. However, for the repeatedly loaded bones, micro-cracking restarts at a lower torque (and twist) than in a preceding load-cycle. For repeatedly loaded bones, the critical torque for further cracking thus decreases with the amount of cracking already formed. The torque and twist at fracture are also smaller for a repeatedly loaded bone of a pair compared to the bone twisted to ultimate fracture in one load-cycle. This also is an effect of accumulation of micro-cracking during subsequent load-cycles. These two effects further support the assumption that cracking occurs during unloading.

Carter & Hayes (1977) have proposed that the mechanism of fatigue-fracture in bone is a progressive accumulation of diffuse structural damage before final fracture. This mechanism is supported by the present study. Through accumulation of damage, the final fatigue fracture may thus occur at a lower load than for a continuously loaded bone.

The residual deformation of the bones can be both plastic and visco-elastic. The time-dependent residual deformation (decreasing almost 50 per cent in 10 min) is typical for visco-elastic properties. When testing machined cortical bone specimens in bending, Carter & Hayes (1977) found similar visco-elastic properties of the bone material. As visco-elastic residual deformation approaches a limit asymptotically, this limit is most probably not attained in 10 min. The limit deformation, if any, corresponds to a residual plastic deformation of the bone but could, however, not be found within the accuracy of the present investigation. A plastic deformation and some part of the visco-elastic residual deformation may occur in the bone ends in addition to a small yielding in the castings (around 0.05 degrees per load cycle according to preparatory tests). The structure of the bone material does not exclude plastic (nor visco-elastic) properties. Microplastic zones around crack tips have been postulated by Robertson et al. (1978) who estimated their size not to exceed 0.02 mm.

In addition to Robertson et al. (1978), Burstein et al. (1972) have proposed plastic properties of bone. Sammarco et al. (1971) and Panjabi et al. (1973) have shown visco-elastic properties of bone, visualized by strain rate-dependent strength parameters. The present work gives further support to the visco-elastic component of bone behaviour.

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