FRACTURE MECHANICS

MICHAEL ALMS, SASKATOON, CANADA

Formerly Orthopaedic Registrar, Bristol Royal Infirmary

The shaft of a long bone may break in a variety of ways in response to different types of violence. Four basic types of linear fracture may be recognised (Fig. 1): transverse, oblique transverse, spiral, and oblique. The violence of the injury may lead to secondary fractures and comminution that tend to obscure the primary failure, but with care this can nearly always be discerned.

Standard works on engineering do not explain satisfactorily the mechanism by which these fractures are produced; to the engineer the actual mode of failure of a material is of less interest than its avoidance. I have therefore attempted to explain, in the light of elementary theory on the strength of materials, occurrences that are familiar to everyone practising traumatic surgery.

The following calculations are applicable to a homogeneous brittle material. Adult cortical bone has a brittle matrix but is strengthened by an intricate fibrous network. To a large extent it behaves as a uniform brittle solid, but sometimes the grain of the fibrous structure is found to modify the expected fracture. Quantitative examination of the strength of bone is made virtually impossible by variations in form and composition of the material. A solid material may be subjected to stresses of compression, traction or shear. Linear fractures may occur in brittle solids in response to traction or shear stresses. Compression may cause linear fracture but this will be brought about as failure in a plane of shearing.

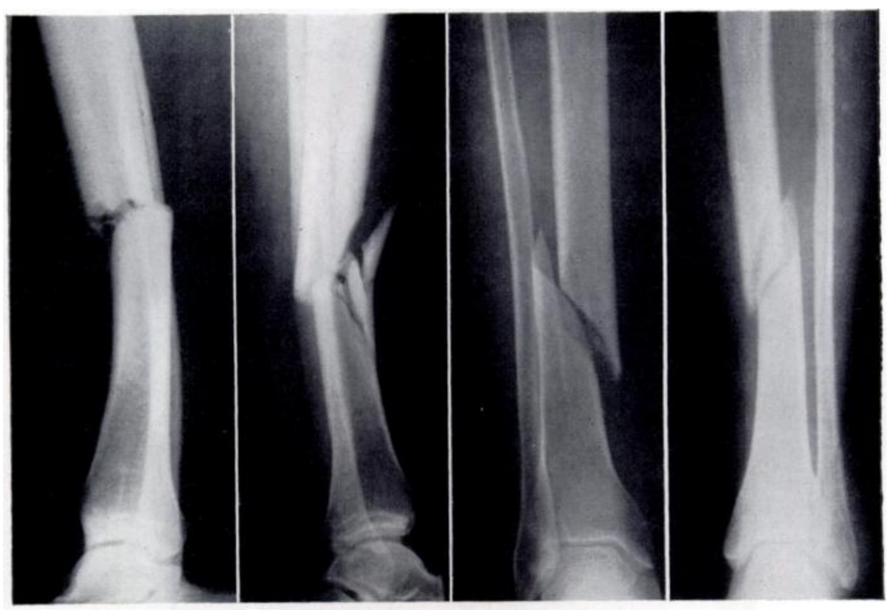

FIG. 1

Four basic types of linear fracture: transverse, oblique transverse, spiral, oblique.

EFFECTS OF DIFFERENT TYPES OF STRESS

The possible ways in which a long bone might fail by linear fracture are considered below, and the type of fracture that would theoretically be produced in each case is considered. It will be found that these conform to the four types of fracture mentioned in the opening

4

paragraph. A careful assessment of the histories of the mechanism of injury in accident cases will verify the theory of fracture mechanics propounded.

Simple traction—This type of stress is most unlikely to be exerted on the shaft of a long bone to the point of failure. Even when the limbs are resisting a tension force, muscle contraction is such that the skeleton is subjected to compression rather than tension. We see this type of fracture in the medial malleolus when a fracture-dislocation of the ankle occurs in eversion. The fracture line is transverse and is typical of failure of a material under tension.

Simple compression—If a pillar be subjected to increasing axial compression it will fail by a linear shear fracture, more or less plane, at an angle slightly steeper than 45 degrees. The axial compressing force can be resolved, at any angle, into a tangential or shearing force and a normal or compressing force (Fig. 2). It is easily shown that the shear stress becomes greatest at 45 degrees, and one might expect failure to occur in that plane. However, the compressive factor modifies the tendency for the material to disrupt. It can be shown that as the plane increases towards the vertical the intensity of the shear factor is at first only slightly diminished while the intensity of the compressive factor falls off rapidly. A plane of greatest weakness occurs at some angle near 45 degrees depending on the nature of the material. Failure, by shear fracture, will occur in this plane.

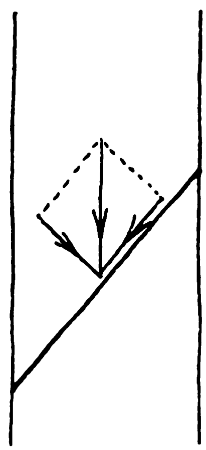

FIG. 2

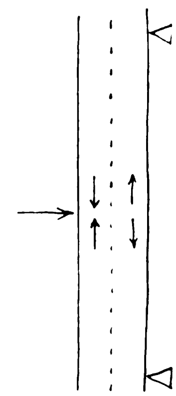

FIG. 3

FIG. 4

FIGS. 2 TO 4

Figure 2—Resolution of axial compressing force.
Figure 3—Stresses in beam subjected to bending force.
Figure 4—Transverse fracture; soft-tissue hinge preserved.

In practice fracture of the shaft of a long bone does not occur under these circumstances. Simple compressive stresses without angulation are rare. When they do occur the cancellous structure of the bone ends fails before the shaft yields.

Bending—If a beam be subjected to bending stresses are set up within it: compression stresses on the concave side and tension stresses on the convex. A neutral plane of zero stress occurs at some level between the two (Fig. 3). If the stress be increased failure will occur, in a brittle material like bone, on the side under tension. A typical transverse crack will appear in that part under greatest tensile stress, the surface of the convex side. This crack diminishes the cross-section area of the beam at this point and the greatest stress is laid on the next layer. The crack spreads across the beam, always occurring in material that is *under tension.* The resultant fracture is therefore transverse.

In practice this type of fracture is seen when a bone that is not bearing weight or stressed by muscular contraction is struck a direct blow. In the tibia this often occurs at football. The soft-tissue hinge is preserved on the side of the blow (Fig. 4). This fracture, like the blow, may occur anywhere in the shaft of the bone.

Bending under axial compression—If a beam be loaded by axial compression during bending the resultant fracture will be modified. If the compression force is insufficient in itself to cause failure, bending will lead to the following situation. Compressive forces will diminish on the convex side of the beam and increase on the concave. Failure may occur by shearing on the side under compression and spread in a plane near 45 degrees across the beam. On the other hand the material might resist failure under compression until the convex side were under such tension stress that fracture occurred on that side in a transverse plane. The

5

fracture would spread across the beam until its cross-section were so reduced that failure would occur under the compression force of the axial loading. The latter part of the fracture would be at the oblique angle typical of this mode of failure. According to the axial stress and the properties of the material so will the proportion of transverse to oblique fracture be determined. As the axial loading increases so will the oblique section be increased at the expense of the transverse until the fracture is entirely oblique.

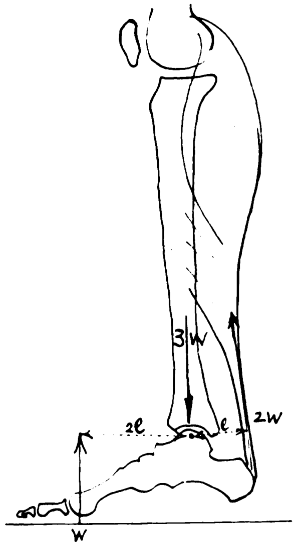

FIG. 5
Stresses in the lower part of the weight-bearing tibia.

In practice this fracture is often seen in the tibia. The bone is usually bearing the body weight and may be stressed also by the far greater forces of muscular contraction and acceleration. (It is worth remembering that in standing on the toes of one foot the calf muscles must exert a force of about twice the body weight to keep the heel elevated. The lower part of the tibia must provide the counter thrust for this contraction besides bearing the body weight. It is therefore stressed in its lower part with about three times the body weight (Fig. 5).) The healthy young adult involved in a road accident, either taking vigorous evasive action, or subjected to violent deceleration, typically shows this fracture. Basically a single curved surface is formed, oblique in part, transverse in part (Fig. 6). Very often a butterfly fragment is formed by the shearing off of the fragment of bone bearing the oblique surface of the fracture. This probably occurs after the primary failure and is due to movement of the main fragments on each other. As the lesser fragment moves and bears on the projecting spur of the major fragment the projection is sheared off through a secondary fracture line which develops in the same way as the oblique part of the primary fracture. According to the axial stress laid

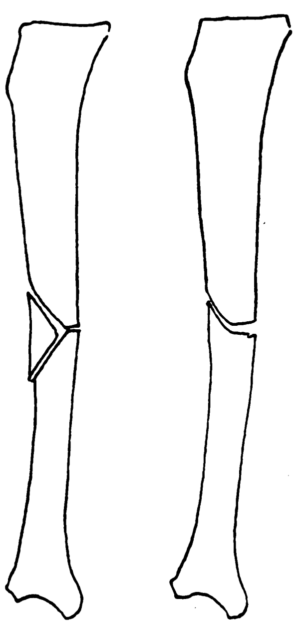

FIG. 6

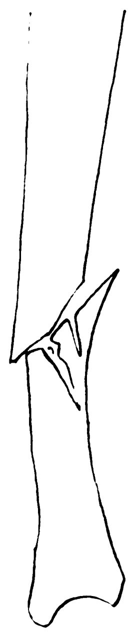

FIG. 7

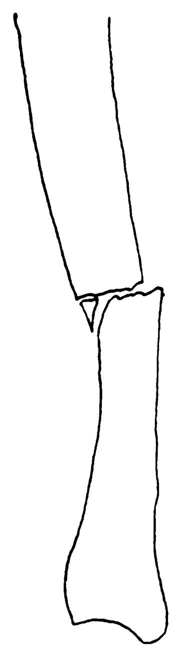

FIG. 8

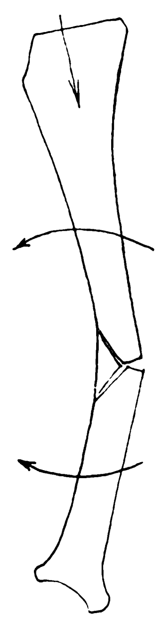

FIG. 9

Figure 6—Components of a single curved surface. Figure 7—Tracing of oblique transverse fracture shown in Figure 1. The fracture line at the posterior border of the tibia is transverse. Figure 8—Tracing of transverse fracture shown in Figure 1. There is an oblique section with separated fragment at the anterior border of the tibia. Figure 9—Failure caused by bending forces, with formation of butterfly fragment.

on the bone at the time of failure so the extent of the oblique section will vary. In practice it appears that the fracture always begins under tension—that is, there is always a transverse element present though sometimes it is very small (Fig. 7). Similarly it seems that there is always an oblique section to the most typical transverse fracture (Fig. 8). This would imply that bone is always under some axial compression. When one considers muscle tension the truth of the observation is evident.

A beam that is bent will fail near the middle and this fracture is seen most commonly at the mid-tibia or at the junction of the middle and lower thirds. Like the transverse fracture it is produced by bending, and the soft-tissue hinge (Charnley 1957) will be formed on the concave side—the side of the oblique fracture and the butterfly fragment (Fig. 9).

Twisting—If a shaft be twisted against resistance a shearing force is established. If the shaft be hollow it is easy to understand the state of shear that is set up in its surface. Failure of a brittle shaft occurs in typical spiral form, the angle of the fracture spiral being about 45 degrees to the axis. In this plane the disrupting effects of shearing factor and tension factor are at their greatest. Failure at one point leads to a rapid spread in this plane until the upper and lower ends of the fracture lie one above the other. The fracture line is then completed by a vertical element between these points (Fig. 10).

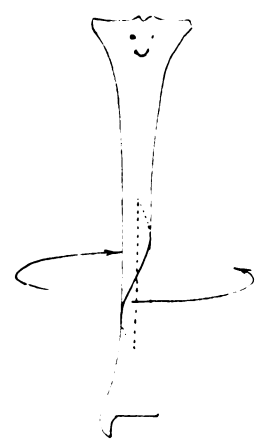

FIG. 10
Spiral fracture produced by twisting forces.

Such a simple twisting force could scarcely occur in the skeleton except in the manipulation of the anaesthetised patient. The usual cause of rotation stresses is the misapplication of the body weight. We should therefore consider the effects of axial loading on the twisted shaft. In Figures 11 and 12 the square represents a unit area of the surface of the shaft. In Figure 11 the rotational shear stress is resolved at a 45-degree plane into stresses of shear and normal tension. In Figure 12 the axial compression force is resolved in the same plane into stresses of shear, in the same direction, and normal compression stress. If the intensity of stress of the two original forces were equal, a state of simple shear would occur at 45 degrees and failure would occur at or near this plane. The greater the axial compression force the more nearly vertical will the plane of simple shear become, but the plane of greatest weakness will never much exceed 45 degrees.

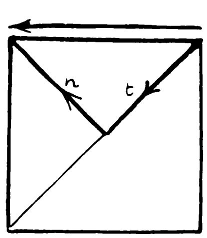

FIG. 11

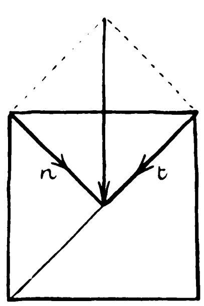

FIG. 12

Figure 11—Resolution of a transverse shearing force into normal and tangential factors at an angle of 45 degrees. Figure 12—Resolution of a vertical compression force into the same factors in the same plane.

The forces of rotation on the tibia are not very powerful and the bone of the healthy young adult is well able to withstand them. If failure occurs it usually takes the form of a fracture-dislocation of the ankle. In this injury the barrel vault of the tibia must rise on the dome of the talus before enough rotation can occur to stress the malleoli. But once this has occurred these small processes are the weakest part of the bone and they fail. In the elderly the bone becomes osteoporotic and its strength is diminished. In a similar twisting accident the tibia can fail before sufficient force has been applied to cause this bone to lift on the talus. The malleoli have not withstood the stress better than the shaft, they have not been subjected to the stress. This explains the prevalence of the spiral fracture in the elderly. Its situation, almost without exception in the lower third of the bone, is because it is a shearing fracture and it is this part of the bone that is subjected to the greatest axial compression under the influence of the calf muscles.