TRANSFERRING LOAD TO FLESH

PART I. CONCEPTS[a]

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MINIMIZING STIFFNESS GRADIENT

Theoretical Principle

Donnell (1) showed mathematically that there is inherently stress at the transition from high to low stiffness [or vice versa] within an assembly when the entire assembly is under load. Others have since expanded this principle to consider bodies of various forms and with various reinforcements or weak spots.

Consider, for example, a sheet of foam rubber with a tensile load uniformly distributed along opposite ends, Figure 1. The rubber will be subjected to a uniform stress in tension on any cross section perpendicular to the load. Now suppose a hole, relatively small compared to the substantially infinitely wide sheet, is cut near the center, Figure 2a. It is well known that there will be high stress concentrations on the sides of the hole, several times the stress in the material far from the hole. The hole is "plugged" with air, far more flexible than even the rubber, so there is a sharp transition in stiffness at the edge and high stress concentration in the neighborhood of the sharp transition or gradient. The rubber stretches more in areas with higher stress, so the hole distorts, Figure 2b. If the hole is the same diameter perpendicular to the direction of tension but longer lengthwise, or elliptical, Figure 3, it may be thought to permit the lines of stress to flow more smoothly around it so that the stresses are not so severe, but there will still be some concentration at the edges. If the hole is elliptical with long axis perpendicular to the tension, Figure 4, or in the worst case a crack across the sheet, Figure 5, the stress concentration is more

[a] This article is essentially a reprint, with illustrations and captions added, of the first portion of a memorandum which Dr. Murphy prepared Oct. 11, 1957, while he was Fulbright Lecturer in prosthetics at the Society and Home for Cripples in Denmark. The document, entitled "Some Thoughts on Fitting of Prosthetic and Orthopedic Appliances to be Checked and Refined," was multilithed and widely distributed by this office to colleagues in prosthetics research, but it has not been previously published.

severe than for a round hole, so propagation of the crack can be stopped or retarded merely by drilling a round hole at the end of the crack to turn the "invisible knife" into a blunted hole; some concentration still remains, of course.

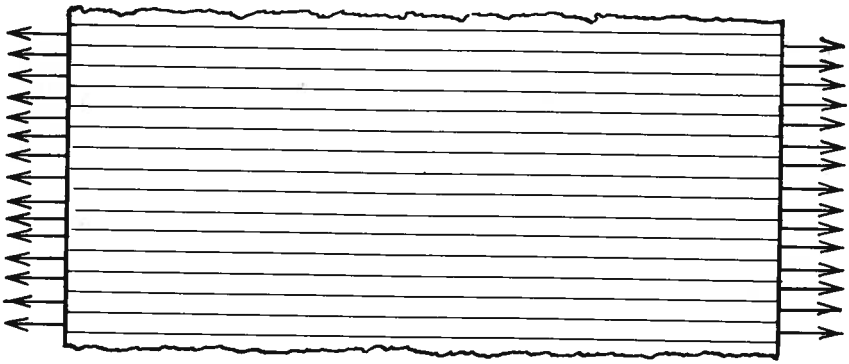

FIGURE 1.—An indefinitely wide sheet of flexible elastic material is uniformly stretched by forces distributed along opposite edges. The sheet may be imagined as a series of narrow bands, each carrying an equal share of the load. The stresses at any vertical cross section are equal.

Now suppose the hole is plugged with a material stiffer than the rubber, Figure 6. The rubber will tend to become narrower and thinner as it stretches lengthwise, in a ratio characteristic of each material (about 0.3 for steel, for example). The relatively rigid plug will prevent this narrowing, so the rubber will compress and bunch up around the sides of the plug perpendicular to the load direction, indicating compression-stress concentration, but will tend to pull away from the plug at the diameter lengthwise to the external load.

If the rubber is cemented to the plug, Figure 7, it will be seen that the compression stress remains at the side but tension stress is concentrated at the ends of the diameter lengthwise to the load. Again, there is stress concentration at a sudden change in stiffness.

These stress concentrations, absent if the plug is the same thickness [and stiffness] *of the same rubber* trephined out but glued back in place, become worse as the plug becomes *either* stiffer or more flexible; in other words, as the stiffness gradient between materials of two different moduli of elasticity becomes more steep. Even a patch of the same material, Figure 8, because it increases thickness and decreases elongation, causes this stress concentration at the edge of the patch (or at the edge of a hollowed-out portion, too, of course). Indeed, the Donnell studies were originally made to investigate failure of gas bags in Goodyear Zeppelins precisely at the *edges* of patches which had been intended to reinforce the bags. A bigger patch merely moved the inevitable stress

concentration to the new edge, although it might conceivably reduce the *basic* stress enough to increase safety. Presumably an effort should be made to sew patches and reinforcements in a staggered manner which

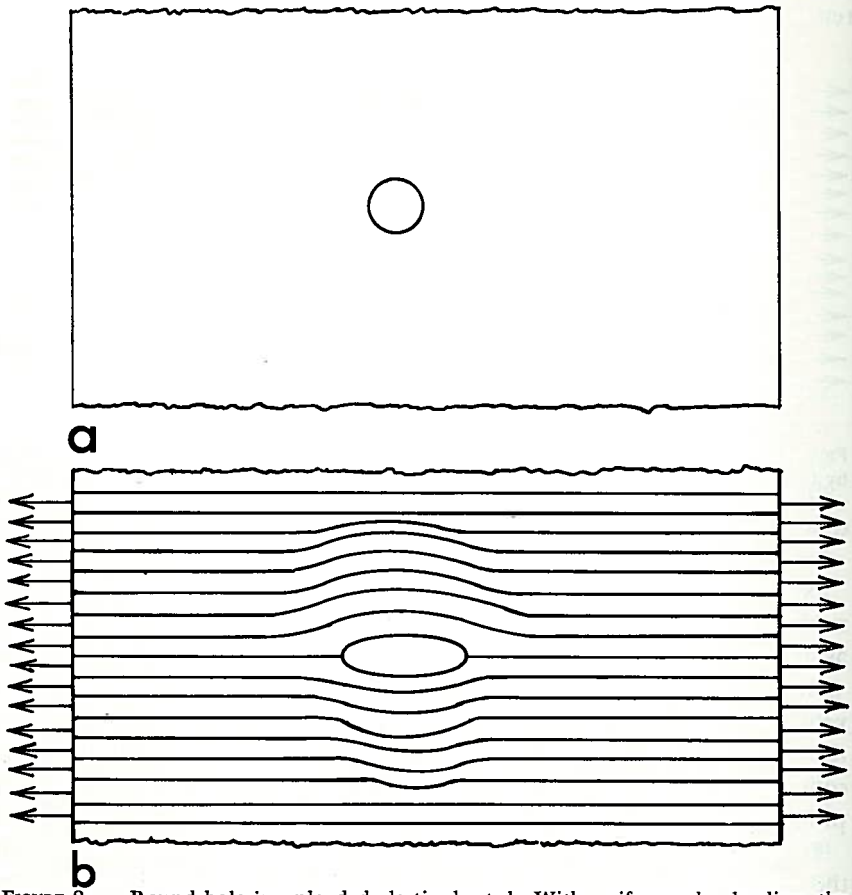

FIGURE 2.—a. Round hole in unloaded elastic sheet. b. With uniform edge loading, the sheet is elongated horizontally. The hole is now elliptical. The imaginary bands, each carrying a uniform share of force at the edges, must pass above or below the hole, not through it, so they are "crowded together" just above or below the hole. There is a higher stress at or near the edge of the hole than at the edges or far away from the hole.

results in a more gradual change in stiffness than a uniformly sewn edge. Excessive stiffening, whether in sewing or in riveting, may actually make the overall assembly weaker instead of stronger by causing a steeper gradient of stiffness at the edge of the supposed reinforcement.

Prosthetic Implications

The usual socket, band, strap, or brace is relatively very stiff compared to body soft tissue, so presumably there is a sharp stiffness gradient

right at the edge of the appliance. Clinically there are typically red marks on the skin immediately after the appliance is removed after heavy loading, there are dermatological complications at the edge (the Levy (2) article in ARTIFICIAL LIMBS showed a number of examples), and the patient may complain more of pressure *at [or at least near] the brim than well inside* the appliance. The *hypothesis* may be offered that these rather frequent difficulties are due to excessive stresses (and deformations) in the skin at the juncture with the stiffer appliance.

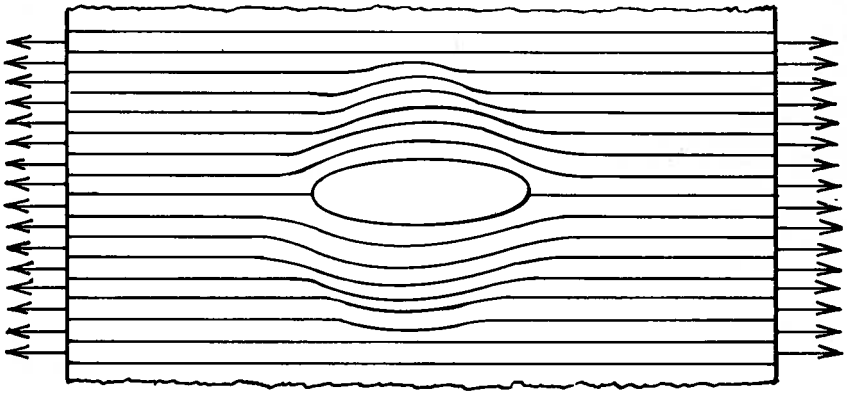

FIGURE 3.—If the original hole in the unloaded elastic sheet were elliptical with long axis parallel to the loading direction, there would be less concentration at or near the hole, illustrated schematically by more "streamlined" patterns of the imaginary bands carrying the edge forces.

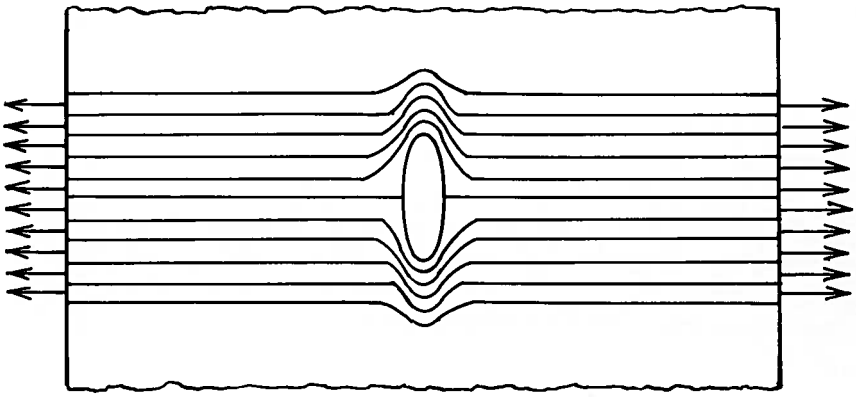

FIGURE 4.—If, in contrast to Figure 3, the elliptical hole in the original unloaded sheet were placed with its long axis perpendicular to the edge loading, there would be very high stress concentration at the top and bottom edges, shown schematically by much closer packing of the bands carrying uniform edge forces.

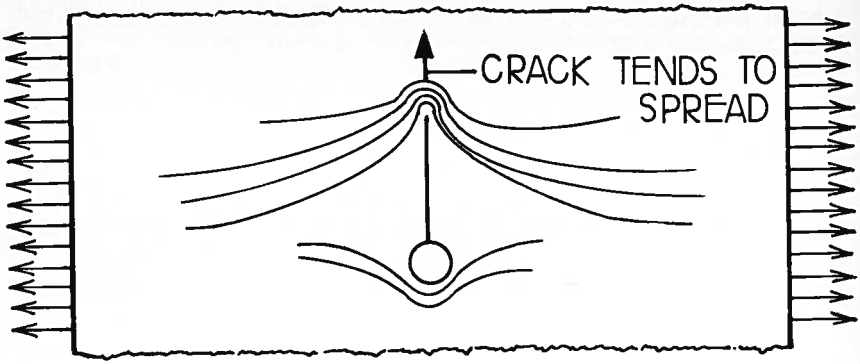

FIGURE 5.—In the extreme case, a long thin ellipse is a slit or a crack. The stress concentration at the end of the crack may be so great as to break the material, causing the crack to spread, especially in a brittle material. This failure can occur even though the stress far from the crack is well below the breaking point. If a hole is drilled at the end of the crack, it will "blunt" the sharp crack, allowing more "streamlined" passage of the imaginary bands and greatly reduced stress concentration. In a ductile material, yielding plastically before breaking, the plastic widening of the end of a slit may produce a similar effect, limiting stress concentration and discouraging crack propagation.

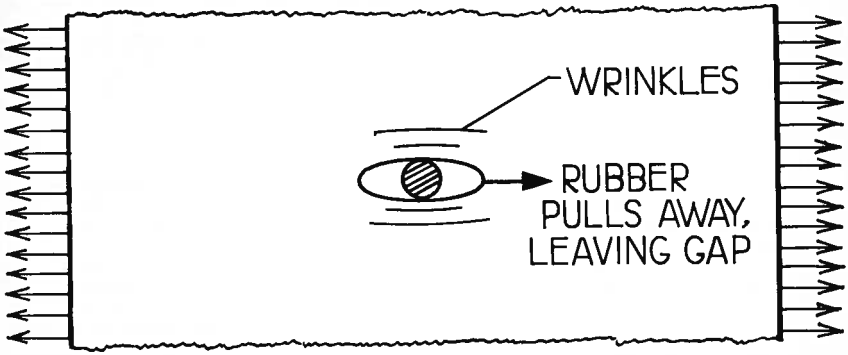

FIGURE 6.—A rigid plug may be fitted accurately in the round hole of Figure 2a. Under uniform edge loading, the elastic sheet can pull away from the plug, so no tension develops at the horizontal edges of the plug. Because the plug prevents the hole from narrowing, there are compression stresses in the vertical direction, perhaps causing bulging, thickening, or wrinkling of the elastic material.

Some Suggestions

The appliance might be made stiff in its central portion, where support is most needed, and in areas necessary to exert the forces creating the bending moments and torques which are shown by biomechanical principles to be inevitable or needed. The stiff sections, composed of any appropriate materials, might then *gradually* change to much more flexible sections near the edges where the appliance stops and unsup-

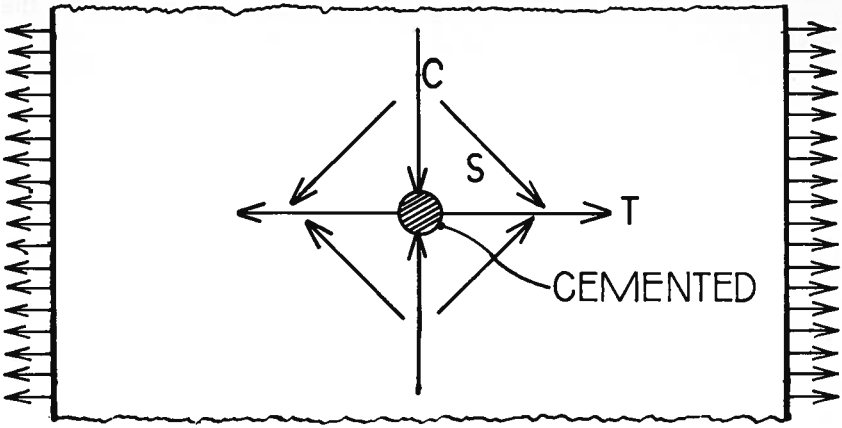

FIGURE 7.—If the rigid plug of Figure 6 is cemented in the elastic sheet, high tensile stresses are developed at and near the horizontal edges, compression stresses develop vertically, and shear stresses develop on 45 deg. planes. These stress concentrations extend appreciable distances from the plug.

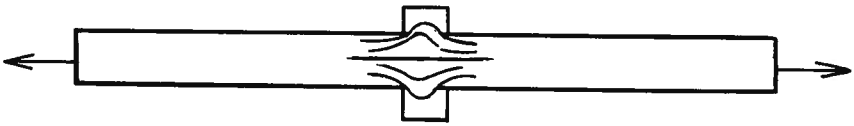

FIGURE 8.—Section through an elastic sheet with thicker integral material (or patches) on top and bottom. This seeming "reinforcement" actually has stress concentrations at its edges.

ported skin continues. This principle of *tapered stiffness* would, one may imagine, apply to sockets and corsets for prostheses, to brace cuffs and straps, to abdominal and back supports, and indeed to many other articles in contact with or in close proximity to the skin—shoes, women's undergarments, nose pieces and temples of spectacles, etc. (In fact, the Donnell principle seems to be demonstrated by the failure first of the springs in the metal wrist watch "strap" links next to the much stiffer watch case, rather than in links far from the case and similar in stiffness to adjoining links.)

In a plastic laminate socket, the central portion might be made of "stiff" resin, many layers of laminating fabric, and Fiberglas reinforcement. Gradually these stiffer elements would be changed, as one proceeded toward the margin, to more flexible resin (since this technique of changing proportions of the mixture of stiff and flexible resin seems feasible), fewer laminations, and no Fiberglas, as well as the thinner cross section resulting from fewer laminations. The edge, of course, should be stiff enough and shaped tangent to the skin so that it will not tend to curl or wrinkle. Further, a material like elastic netting, such as

that used for girdles, might be fastened along the edges to decrease the gradient further.

In a strap (of leather, for instance) the edges might be skived or bevelled so that support would occur chiefly in the central portion with a gradual tapering toward the edges. A tight strap of rectangular cross section, by clinical observation, leaves red marks on the skin at the edges, not in the center; according to the above hypothesis, these marks noted immediately after removal of the strap are due to attempts of the body to repair minor damage from local stresses due to the sudden change in stiffness.

Merely rounding the surface in contact with the skin, as is done in watch cases, in truss buttons, and in nose pieces of spectacle frames, is a slight step in the direction suggested, providing a tapering-off of support toward the rim.

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