SKIN TISSUE CUTTABILITY AND ITS RELATION TO LACERATION SEVERITY INDICIES

BY

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INTRODUCTION

Injuries to the head and face from glass in traffic collisions have been recognised for many years and various treatments of windscreen glazing have been developed to diminish the problem. Laminated safety glass was first manufactured by a French company, La Société du Verre Triplex in 1909, and from the 1930s some form of laminated glass was used in windscreens in many parts of the world. At around the same time the tempering of glass sheet by a heat treatment process was perfected, so that two quite different solutions to the problem of injury reduction from glass evolved over the years.

The introduction of better moisture control and a thicker interlayer in laminate greatly improved the collision performance of laminated glass in the 1960s, so that now it is the preferred material from the safety point of view, even though it is more expensive than toughened glass.

The frequency of head and face contacts with windscreens has been established in a number of in-depth accident studies. Normal windscreen contacts only occur in frontal impacts which, for samples of accidents which result in an injury to at least one occupant, represent 58 to 70% of all collisions. A U.K. study (Hobbs, 1980) showed that in frontal impacts, the incidence of head and face contacts with windscreens for unbelted front seat occupants was 18% for drivers and 40% for passengers. Those frequencies drop to 3% for drivers and 4% for passengers if seat belts are worn. A similar study (Mackay et al, 1981) showed for frontal impacts on a front seat occupant base, if unrestrained, some 41% had some contact with the windscreen and that number was reduced to some 6% if seat belts are worn.

A French study (Fayon et al, 1979) of frontal collisions showed that 24% of unrestrained drivers were injured by the windscreen, whilst 45% of front seat passengers were similarly injured. The great majority of the cars in that study had toughened glass windscreens.

A United States study (Malliaris et al, 1982) ranks the windscreen third, behind only the steering assembly and the side interior surface, in terms of the components causing the most "harm" in the NASS data file. "Harm" is the product of the dollar cost of the injury by severity and their frequency. All the windscreens in that study were HPR laminated, and virtually all of the injuries were at the A.I.S. 1 level.

Field accident studies of injuries from laminated glass therefore indicate that although the injury severities are minor in overall terms, they are frequent enough to constitute a significant problem. Those injuries can be classified as either soft tissue lacerations or deceleration injuries leading to some cerebral concussion.

Detailed studies suggest that concussion from simple contacts with a laminated windscreen occurs rarely (Mackay and Smith, 1981). Of 50 precise head contacts, 44 generated some soft tissue injury and 3 caused minor concussion. The investigation of this question requires careful evaluation of the contacts which an occupant makes. These may be with structures other than the windscreen, such as its frame, so that the head strikes a metal surround as well as having a genuine impact against the glass, and often such multiple contacts are overlooked, with the result that the risk of concussion from laminated glass can be overstated.

The main problem illustrated by accident data therefore is facial laceration, and this study explores the relationships between the cuttability of skin and laceration severity indices which have been used in the past to classify the injury potential of windscreen glazing.

Specifically we describe test results, obtained with a simple dropping impactor rig, on the cut depth produced by sharp edge impacts on a variety of skin tissues. A comparison of the performance of human skin to that of commonly used skin simulations is made, as an attempt to quantify the relationship between the damage observed in laceration testing with these simulations, and that expected on real human tissue.

The variability of the tissue could also be examined; human skin was found to vary by a factor of two in its strength, dependent to some extent on the age and thickness of subcutaneous fatty tissue present. Natural skin simulations appear slightly less variable.

The material properties under the experimental loading conditions are examined and used to interpret the impact forces generated in terms of a material stress. By expressing the results in terms of a material property, a general performance criterion is sought which can be applied to a general loading configuration such as those found in accidents. Using this scale, a statistical scheme for comparing the results of laboratory tests with real accident data is developed.

METHOD

A dropping impactor facility based on that used by Leung et al (1977) was used to subject samples of natural skin tissues to sharp edge impacts. The impactors presented, at the impact site, edges of width 10 μm formed by flanks intersecting at angles of 30, 60 and 90 degrees. The edge profile was regularly monitored so that blunting and localised damage of the edges would not affect the results.

At each sharp angle, two or three different lengths of cutting edge were tested and the peak force generated per unit edge length during the impact was used as the physical severity parameter to compare the cut severities produced. To verify that the controlled edges of the manufactured impactors were similar to those causing injury in head to windscreen contacts, a 90 degree glass edge was prepared from a freshly fractured piece of float glass. This performed in an identical fashion to the other 90 degree edges used. It was found impossible to prepare a glass edge from free fracture, suitable for these tests, at any other sharp angle.

The force pulse occurring in the impact was measured by an accelerometer mounted in the impactor assembly, and recorded in digital form on a paper tape which formed the input to a computer program allowing the peak force generated, energy dissipated, force/deflection behaviour and other physical parameters to be accurately examined at leisure.

The damage sustained by the tissue was assessed as cut depth from a comparative procedure. Close examination of several cuts in chamois leather of 1mm thickness revealed that ten distinct degrees of cutting could be distinguished with an accuracy of ± 1 degree; thereby allowing cut depth to be 'measured' to an accuracy of ± 0.1mm.

SAMPLES TESTED

Three types of skin were examined; post-mortem human skin from two different body sites chosen as similar, in medical opinion, to facial skin, chamois leather and napa-goatskin, both commonly used skin simulations in safety testing.

Eighteen samples of human skin from the anterior aspect of the upper thigh were tested with all the available impactors, while twelve samples from over the scapula were tested with just a single impactor in an attempt to better identify the influences of biological variables such as age, sex and fat structure on the cut resistance. Chamois leather was tested in the wet state used in laceration testing while napa leather was tested dry, again as used for laceration measurements. Because of the different manufacturing techniques, napa leather has two distinct sides, unlike chamois, both faces were separately subjected to cutting impacts.

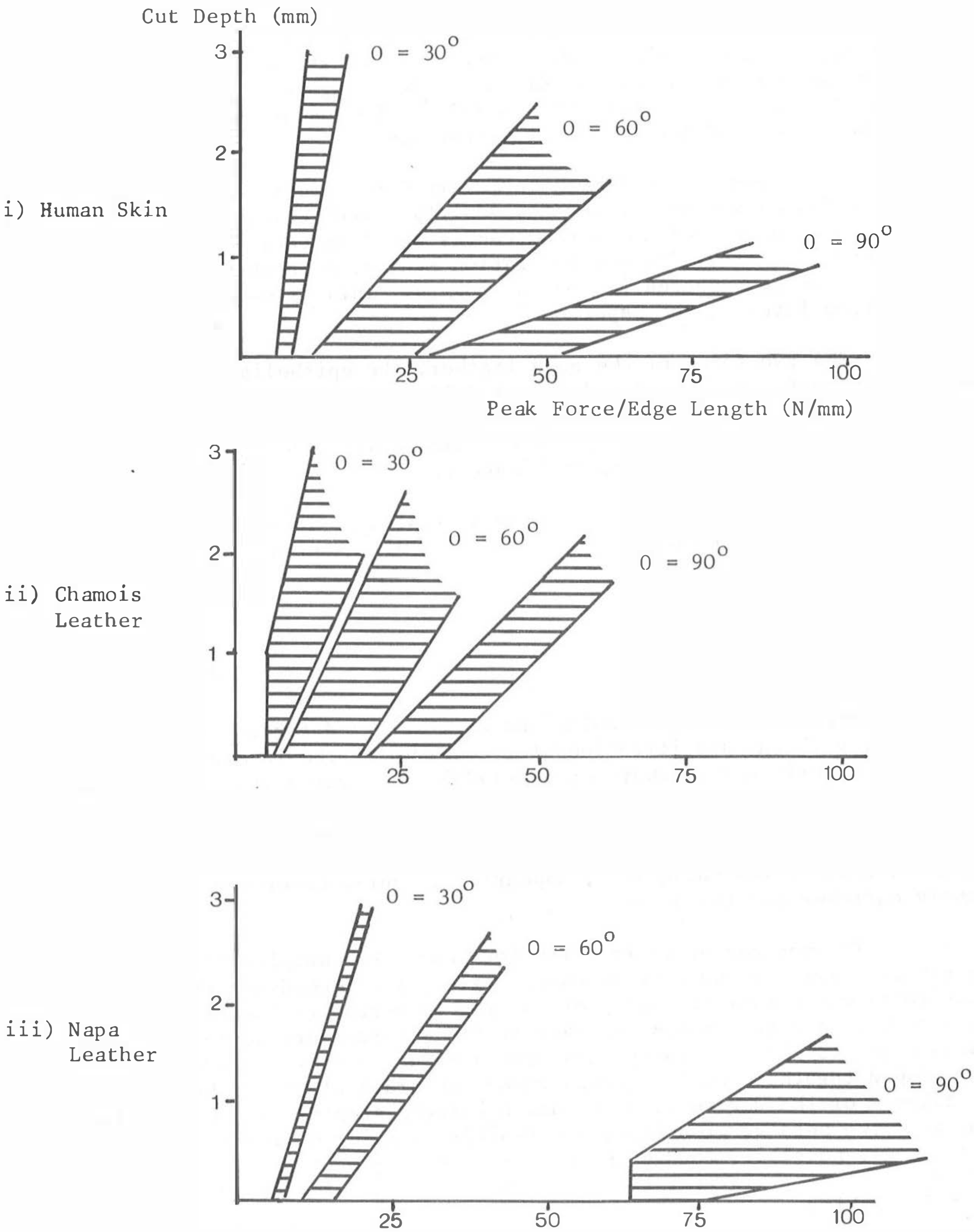
The human skin samples were not trimmed so a quantity of subcutaneous fat was present on each, varying from virtually zero to several millimetres in thickness.

RESULTS

The results of the tests were represented as plots of cut depth against peak force per unit edge length. These plots show a band of increasing cut depth with increasing force, the maximum force attainable without damage to the skin itself increasing with the sharp angle. All impactors with the same sharp angle performed identically when the edge length was taken into account on this plot.

Performance bands were constructed from the 'x' on 'y' and 'y' on

FIGURE 1 Performance Bands for Skin Tissues



'x' least square linear regressions, it is these bands which are presented in Figure 1. Usually some 90% of the data points lie evenly distributed within this band.

Although all three skin tissues have bands in a similar range of impact forces, there are notable differences. The pattern of behaviour displayed by human skin is condensed into a smaller range of forces for the chamois leather, while the napa leather shows a larger than usual difference between the 90 degree edges and the more acute impactors.

From these plots it can be inferred that when skin simulations are subjected to forces sufficient to cause fairly severe tissue damage, say 25 to 50N/mm, human skin in the same circumstances would sustain much less severe damage. Thus laboratory devised laceration scales, overestimate the tissue damage which can be expected in real accidents. This is more closely examined and quantified later in the paper.

The two faces of the napa leather, the epithelial grain and the dermal flesh surfaces, showed a distinct difference in performance. Though statistically of marginal significance, an unmistakable tendency for the flesh surface to be stronger than the grain is discernible. Both sets of results were used to construct the plots in Figure 1.

The two sites from which human samples were taken performed very similarly, and are both used in Figure 1. The differences observed between the sites is discussed below.

TISSUE VARIABILITY

The natural skin simulations were selected for condition and thickness according to the specifications for determining the laceration severity index 'TLI' described by Pickard et al (1973). However a wide range of cutting strength is evident from the width of the performance bands. In spite of its non-reversible nature, the napa leather shows a narrower spread, at least for the more acute edges, than the chamois. The width of the chamois bands is similar to that of the human skin, appearing slightly wider for acute edges and slightly narrower for the obtuse.

The sources of variability for human skin samples were examined in more detail. For the two extreme sharp angles, the dependence of cut depth on impact force was either too steep or shallow to certainly identify any strength trends from sample to sample; however at the intermediary angle, two ranking methods were possible. Firstly sampleswith visually similar performance curves were grouped together and the groups ranked in order of strength. A statistical analysis of the degree of association between samples was then conducted. From these two sets of groupings, a definitive ranking of individual sample strengths was possible, though the quantitative scale of the ranking was not defined. Biological variables could then be examined for trends associated with this ranking.

Initial studies using only part of this procedure (Careless and Acland (1982))identified only the hairiness of the skin as causing a shift in the strength, difficulties in quantifying this factor precluded further examination of this possible effect.

Three parameters were especially examined in this analysis, the thickness of subcutaneous fat, the age and sex. For samples from the site on the leg, age was the major factor; a correlation statistically significant at the 1.1% level was evident, with younger skin appearing stronger. With samples from the scapula however, the thickness of fatty tissue gave the best correlation, a 2% significance level, with no correlation to age at all. A marginally significant (8% level) correlation to thickness was also seen for the first site. No sexual trend was discernible for either site.

The different sources of spread between the two sites can be explained in terms of the structure of the fatty tissue. For the first site the adipose tissue is loose and essentially structureless, appended under the skin in unaglomerated lobules which can readily be shifted away from sites of localised loading; in contrast, fat with samples from the second site was dense and laced with tough dermal membranes. The more structured tissue will inevitably be more able to contribute to the generation of forces during the impact, thus more force will be required to generate within the skin itself, the critical stress conditions responsible for cutting. The trend of increasing strength with increasing thickness can thus be anticipated.

Notwithstanding the above observations, the contribution to the total force from the deformation of the fatty tissues is relatively small; 2% at most. Further the overall spread in performance at the two sites is very similar. The forces measured can thus be seen as indicative of the loading conditions in the skin proper, the consequences of the contribution from the fat are felt primarily in energy absorption. The long low modulus compression of the fat absorbs much more energy than the high modulus compression of the skin itself. This can be quantified as a 100% increase in the energy needed to achieve a given force level for each extra 2mm of fat. In short, the bulk of the energy is absorbed by the fat while the bulk of the force is generated by the skin.

MATERIAL PERFORMANCE

The force parameter used in Figure 1 is subject to influences from the skin's thickness, the material deformation properties and the geometry of the impacting edge. As such the performance bands are specific to the particular conditions of the test. To obtain a general picture of the relative behaviour of the tissues under cutting loads, a model of the skin's deformation up to the initiation of cutting has been constructed. This depends primarily on the force/deflection characteristics of the tissue under normal compression, though for the most acute edges, the tensile behaviour of the fibrous structure is also important.

Using a flat tip mounted on the impactor assembly, the materials' constitutive equations in normal compression were determined. Following the precedent of North (1972) and McElhaney (1972) these were represented by a power law:

$$(\text{stress}) = \text{constant}\ (\text{strain})^{n}$$

Incorporating data due to Daly (1966) and Stark (1970) on the tensile properties, the measured impact forces can be interpreted in terms of the shear stress experienced by the fibres at the edge tip. On this material parameter scale the geometric differences between impactors is greatly reduced, and a single performance band can be constructed for each skin type, thereby supporting the generality of this scale.

This analysis reveals one important feature of the cutting. Gadd et al (1966) amongst others expounded the idea of two distinct modes of cutting; this work demonstrates that these are just alternative methods of generating the same stress conditions. In impacts with the more obtuse edges, critical shear stress is generated through compressive reactions within the bulk of the material. For more acute edges shear is developed by fibre tension in a free tissue surface, and not primarily by reactive forces. This fibre tension mode of failure is not very dependant on the material properties while the reactive shear is. Thus empirical cut tests which rely on sharp edge contacts such as razor blades are unlikely to detect any material differences between skins. The type of edge being investigated in safety research can consequently influence the choice of methods and interpretation of results. In the particular case to be discussed below, of injuries from laminated windscreens, the tissue under stress will be considerably compressed through head contact with the screen, and most of the injury producing edges are of large (around 90 degrees) sharp angle; the material properties will thus have a major effect on the cut severity since reactive forces will contribute most to the shear generation. However if injuries from, say, flying glass splinters are being studied, the material will have only a small effect on the results provided the material's basic fibre strength is similar to that of human skin.

The shear stress performance bands are shown in Figure 2. In all three cases, small though inconsistent geometric differences remain which can be attributed to quantitative uncertainty in the constitutive parameters, and to the simplification necessary in the deformation model.

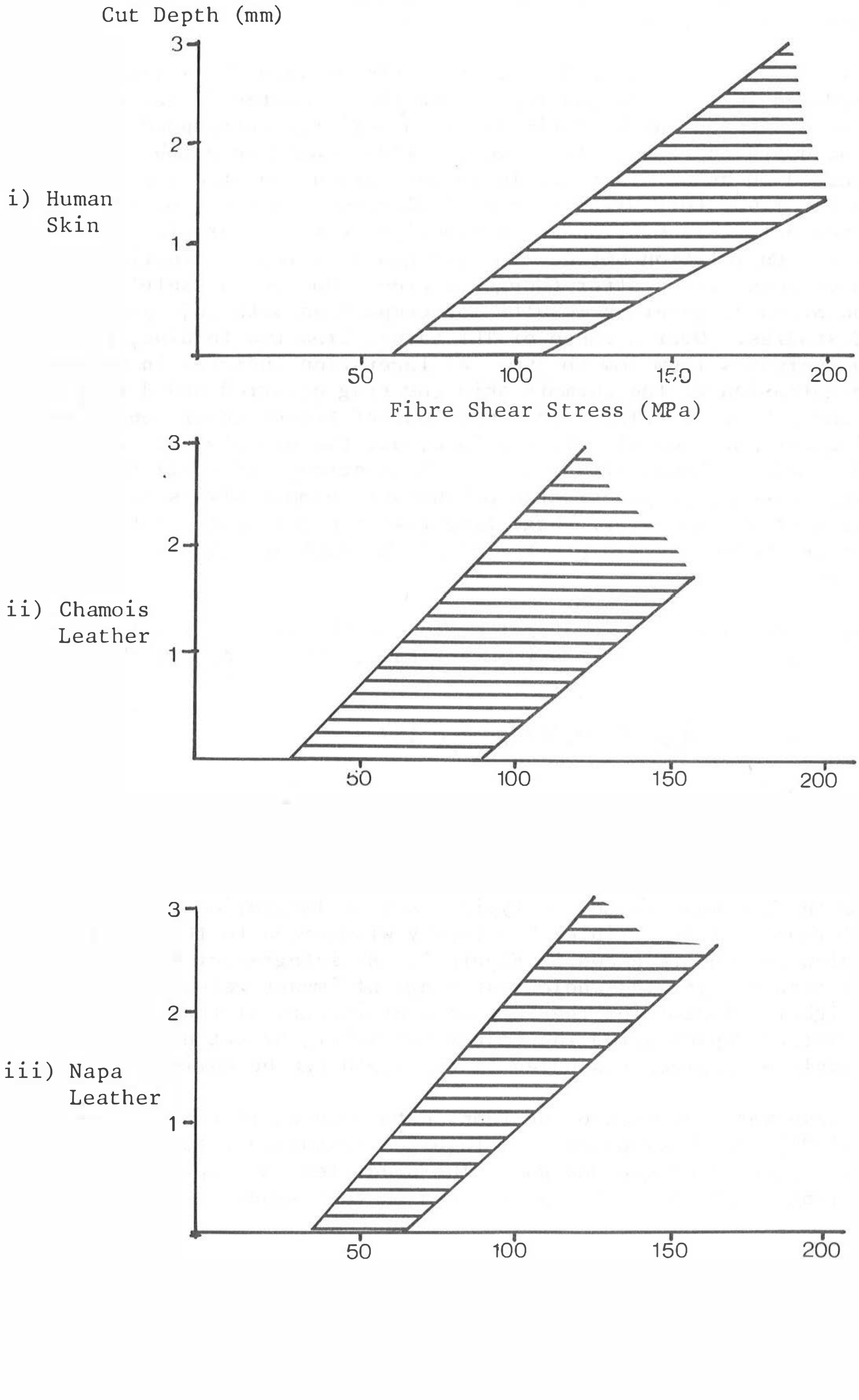
The magnitude of the fibre fail stress given by the performance band position at zero cut depth, is similar though rather less than, the strength of pure collagen fibres which are known to disrupt at tensile loads in the range 150-300MPa, that is shear loads of 75-150MPa (Harkness 1968). The difference is accounted for by remaining spaces within the fibre structure and partial failure of thicker fibres due to localised bending.

LACERATION SEVERITY

During a laceration producing impact onto a structure such as a laminated windscreen, skin tissue will suffer a range of sharp edge contacts each generating a fibre shear stress dependant upon the geometry and dynamics of the impacting surfaces. In real impacts the distribution of individual contact stresses is unascertainable. In the absence of this knowledge, a distribution of stresses at equal propability up to some maximum will provide a suitable model for investigating the expected severity of cutting to different tissues under the same impact conditions.

Given this distribution, the average cut depth can be calculated

FIGURE 2 Shear Stress Performance Bands



from the performance bands of Figure 2; the results from different tissues can then be compared. This is done in Figure 3. As can be seen here the tanned skins behave similarly, both being cut to a much larger average depth than human tissue, at the same maximum stress.

From the curves in Figure 3 a relationship between the average cut depth actually produced in a lacerating impact and that expected in the same impact with some other tissue can be derived. If a definite correspondence between average cut depth and laceration severity index could be established, the cut depth expected on human tissue could be determined from the laceration index measured in the laboratory using tissue simulations. Studies of results from several hundred actual laceration tests reveal that such a precise relation does not exist. Correlation between TLI and two different definitions of average depth can be seen, the scatter though is wide. However a useful linear relation can be obtained to generate results for comparison with injury scales derived from field studies. Over a range of TLI values from two to nine, the average cut depth increases from 1mm to 3mm. At laceration indicies in excess of six complete penetration of the chamois skin covering occurred and damage was sustained by the rubber underlay. The behaviour of tissue under conditions of skin penetration has not been closely examined, but the underlaying material in both human and simulated human tissue is much less strong and stiff than the skin. In drop impacts complete penetration of the skin almost always leads to complete penetration of the underlay, suggesting that the cut depth in these circumstances is more limited by the protrusion of the cutting edge away from the bulk of the screen.

The non-penetrating range of cut depths in the sample from laceration tests, corresponds to a range of maximum stresses, 96-140MPa; in this range:

$$\bar{d}_{HS} = 0.547\bar{d}_{ch} - 0.187$$

and

$$\bar{d}_{ch} = 0.363\,TLI - 0.347$$

Laboratory evaluated TLI/impact velocity curves can thus be described in terms of expected cut depth to human tissue. A typical set of laceration curves comparing the performance of the Triplex Ten-Twenty windscreen to that of a conventional annealed screen are shown in Figure 4. By integrating the distribution of these results over the whole test range of impact velocities, together with a weighting factor for the incidence of impacts at that speed, a frequency distribution representing the injury potential, or cut depth, expected from a sample of accidents studied in the field can be derived.

This scheme was exercised on accident data previously reported by Mackay and Smith (1981), which compares real injuries sustained after contacts with the two above-mentioned screen designs. The predicted cut depth compares well with the description of the injury scale used in this study:

FIGURE 3 Average Cut Depth to Skin Tissues in Laceration Producing Impacts

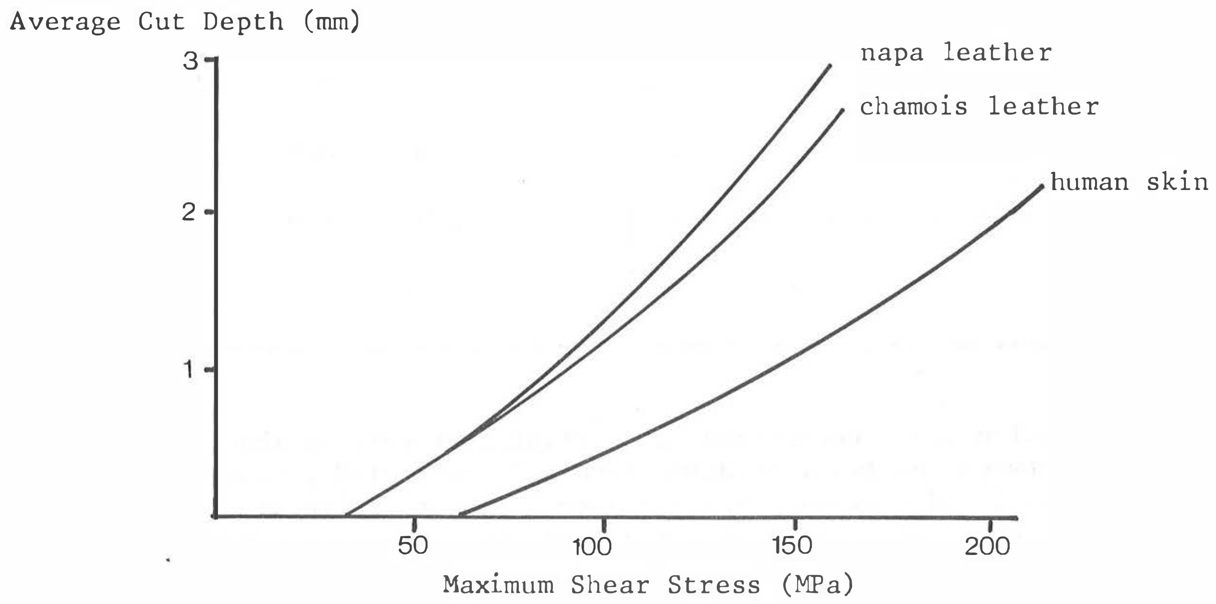
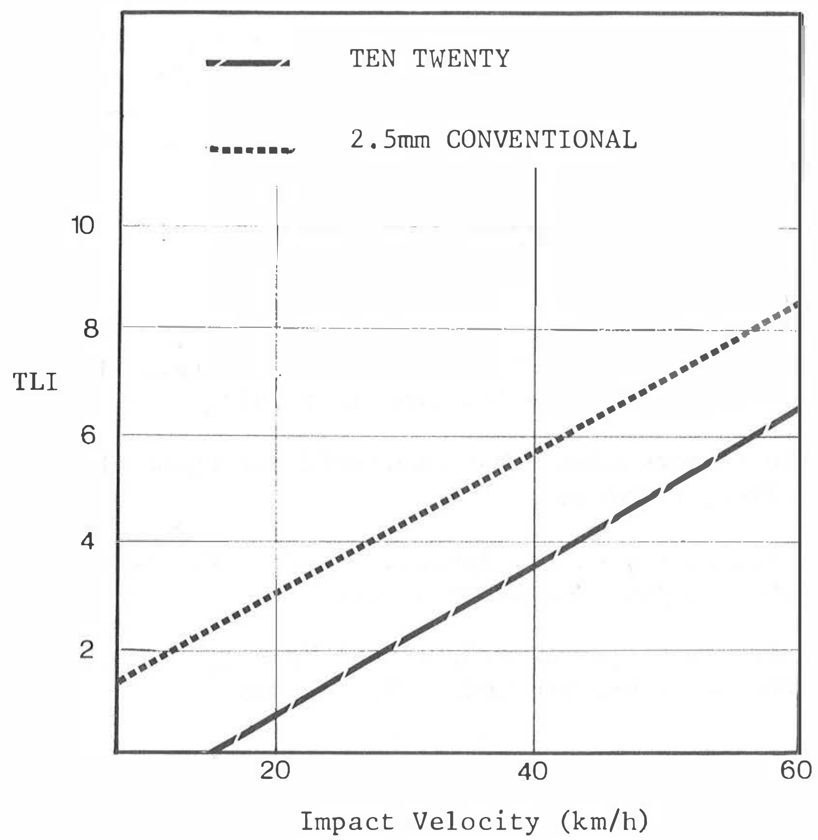


FIGURE 4 TLI as Function of Impact Velocity (after Kay et al 1973)



Injury Category		Predicted Average Cut Depth (mm)
none reported	= 2	0
'bump' or bruising	= 3	0 - 0.1
minor abrasions	= 4	0.1 - 0.5
laceration (no stitches)	= 5	0.5 - 0.8
laceration (stitches)	= 6	0.8 -

The minor abrasion level corresponds to cutting just through the epidermis, the distinction between the two laceration levels is less clear, though cuts of around 1mm deep would certainly produce bleeding; it is important to recall that the predicted depths are averages and the most severe cut may be somewhat deeper. Also important is the severity of the injuries. As already noted, windscreen lacerations are generally a 'minor' injury (AIS 1 or 2); the testing and analysis is concerned with this severity of cutting and extrapolation to higher severities is not strictly justified. Cutting below the skin proper has rather different physical characteristics.

This statistically based analysis of laboratory data, utilising accident velocity distributions and material performance parameters provides a means of interpreting arbitrary injury potential scales such as the TLI in terms of real injuries, and thus real injury reductions associated with changes observed in these indicators.

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