CAR FRONTAL CRUSH - A NEW PERSPECTIVE

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ABSTRACT The full width barrier, 45% overlap rigid barrier and 30 degree angled barrier behaviour of 8 cars is examined in terms of their force/dynamic displacement and energy absorption/dynamic displacement responses. This shows that the car front under full width crushing can be divided with increasing crush depth into 3 regions, each of which can be regarded as having constant crushing forces. The 3 regions are associated with the car longitudinal members, the engine/rear front structure and the occupant compartment. The data shows that the longitudinal members and the occupant compartment crush at lower force levels than the engine/rear front structure. The car responses indicate that the car manufacturers have the potential to reduce the extent of occupant compartment intrusion by increasing the rigidity of this part of the car structure.

THIS PAPER EXAMINES the frontal crushing behaviour of eight cars in full width and 30 degree angled barrier tests at 56 km/hr and in 45% overlap rigid barrier tests at 50 km/hr. The purpose is to obtain an insight into the overall crushing behaviour of car front structures and the manner in which this behaviour varies with depth of crush. The evaluation is carried out in two ways, firstly the acceleration/time responses are transformed into acceleration and force/dynamic displacement responses and secondly the absorbed energy/dynamic displacement responses are obtained. The absorbed energy/dynamic displacement responses are the integration, as a function of dynamic displacement, of the force responses and act as filtering mechanisms averaging the forces and which highlight sustained gross changes in the crushing behaviour of the car fronts. Fossat (1994) examined the force/time full width frontal crush behaviour of a number of cars and showed that the time response can be divided into two distinct constant force regions, an initial low force region followed by a second, high force region.

METHOD OF ANALYSIS

For the purposes of comparison between cars the dynamic crush was normalised with respect to overall length of the cars, (d/L), while the absorbed energy was normalised in terms of energy absorbed per unit mass (E/M). This latter term, used in the evaluation of the energy absorption efficiency of structures (Thornton et al, 1983), is called the Specific Energy Absorption, and is in units of Nm./kg. The acceleration and force responses were normalised in terms of the energy absorption per unit depth of crushing. This is the Specific Energy Absorption Capacity, (Thornton et al, 1983) and is equivalent to (F/M).L where L is the length of the car and has units of Nm/kg. This factor is the theoretical maximum amount of energy the structure could absorb if it was capable of being crushed over its full length with the same average crushing force. Wood (1991, 1992) has shown that the overall frontal crush characteristics of cars when normalised as above are similar and that the overall car population can be characterised by a general relation between Specific Energy Absorption and normalised crush depth (d/L).

VEHICLE DATA

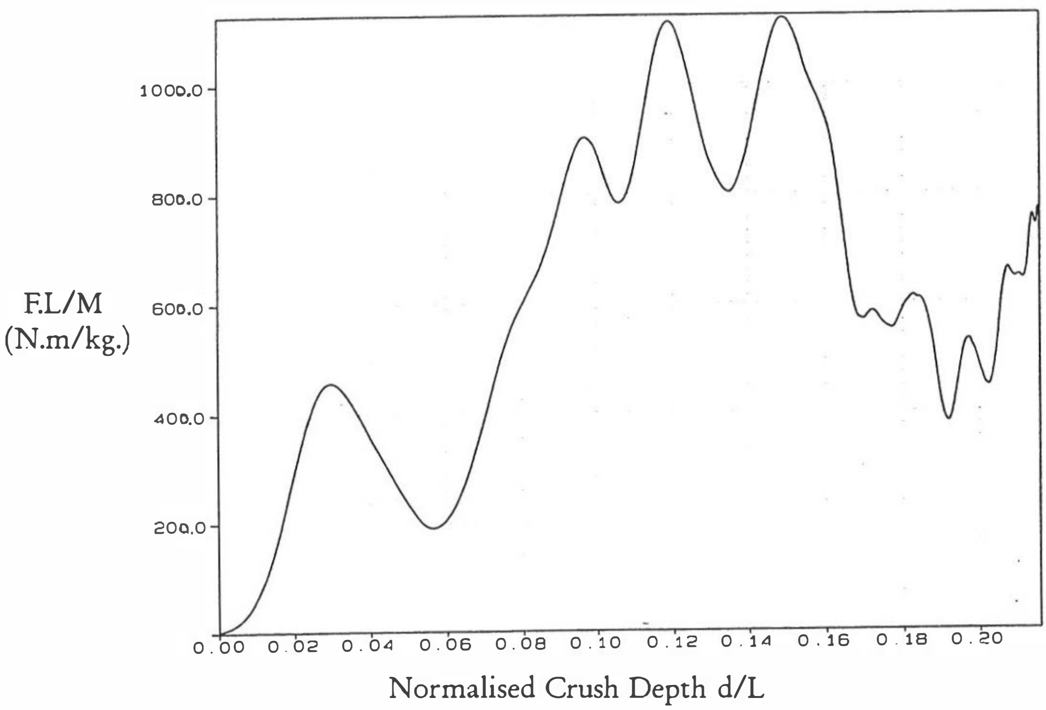
The characteristics of the cars analyzed are detailed in Table 1. All are front wheel drive and with the exception of car 3 which has a longitudinal engine all have transverse engines.

Table 1 - Vehicle Data

Car	Curb Mass kg.	Length m.	ds/L	de/L	db/L
1	860	3.96	0.033	0.081	0.220
2	809	3.96	0.045	0.091	0.250
3	1010	4.41	0.030	0.059	0.249
4	810	3.63	0.030	0.094	0.218
5	1090	4.56	0.026	0.103	0.208
6	990	4.41	0.035	0.084	0.236
7	745	3.70	0.052	0.086	0.238
8	1260	4.71	0.074	0.128	0.244

The ratios ds/L, de/L,and db/L are the normalised distances from the fronts of the cars to the start of the two longitudinal members in each car, the front of the engine and the front of the bulkhead/firewall which divides the occupant compartment from the car front structure.

Figure 1. Full Width Rigid Barrier Response - Car 4.



BEHAVIOUR OF CAR 4

Figures 1 to 4 show the responses of this car. Figure 1, the full width response, shows that the crushing force increases to a peak at d/L of 0.03, drops to a minimum at d/L of 0.06, then rises rapidly and oscillates about a high force level. At a crush level, d/L, of 0.16, the crushing force drops to a lower force level.

Figure 2. 45% Overlap Rigid Barrier Response - Car 4.

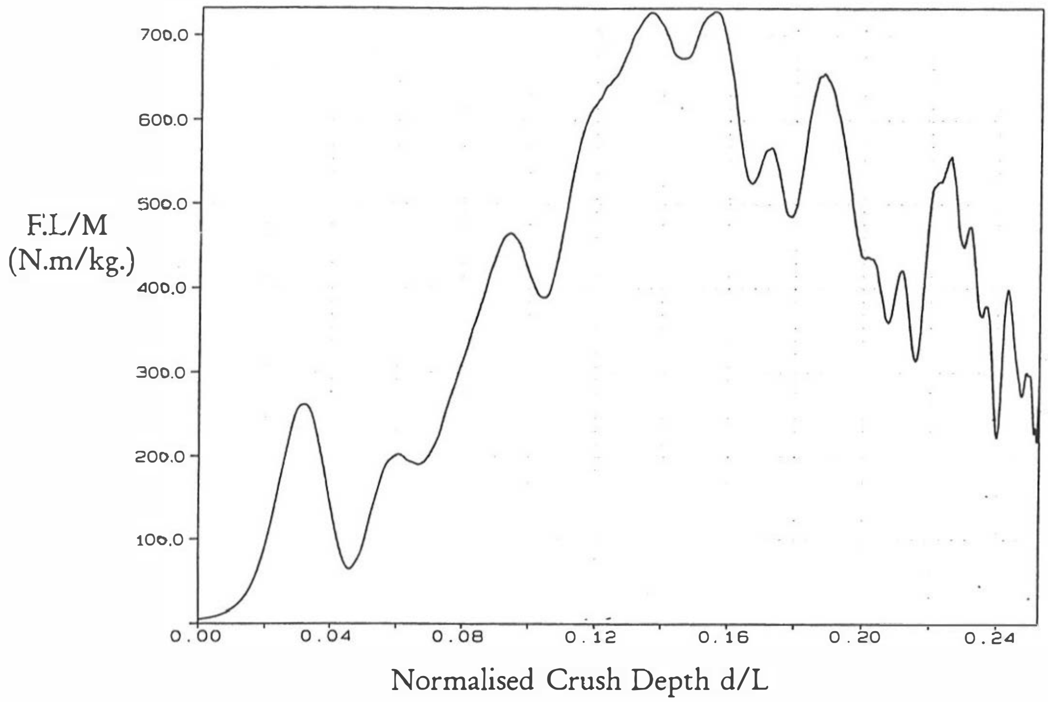


Figure 3. 30° Angled Barrier Response - Car 4.

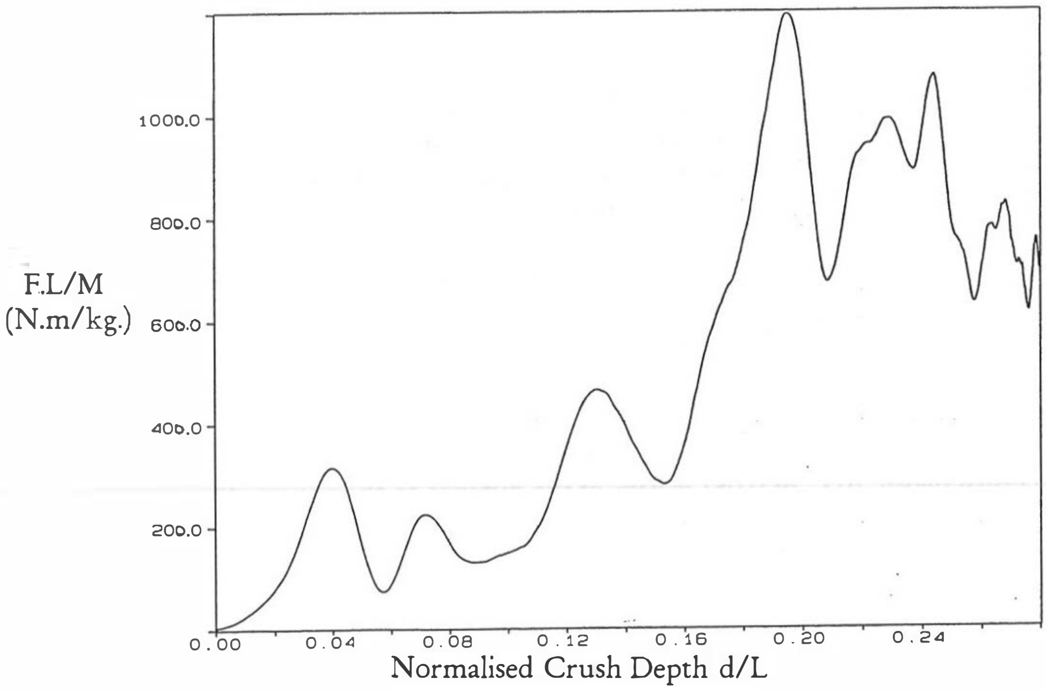


Figure 2, the 45% overlap rigid barrier response, also has an initial force peak at d/L of 0.03, falling to a minimum force at a crush, d/L of 0.045. This is followed by a gradual rise in crushing force up to a plateau from which it begins to fall at a crush depth, d/L of 0.16. From this point the force continues to fall up to the maximum dynamic crush of d/L of 0.252. Figure 3 shows the 30 degree angled barrier response. The crushing forces are of a low level until a crush depth, d/L, of 0.11 is reached after which it rises reaching a high level and oscillating about it at crush depths between 0.18 and 0.25 after which it sharply drops and levels out at a lower force level.

Figure 4. Full Width Absorbed Energy Response - Car 4.

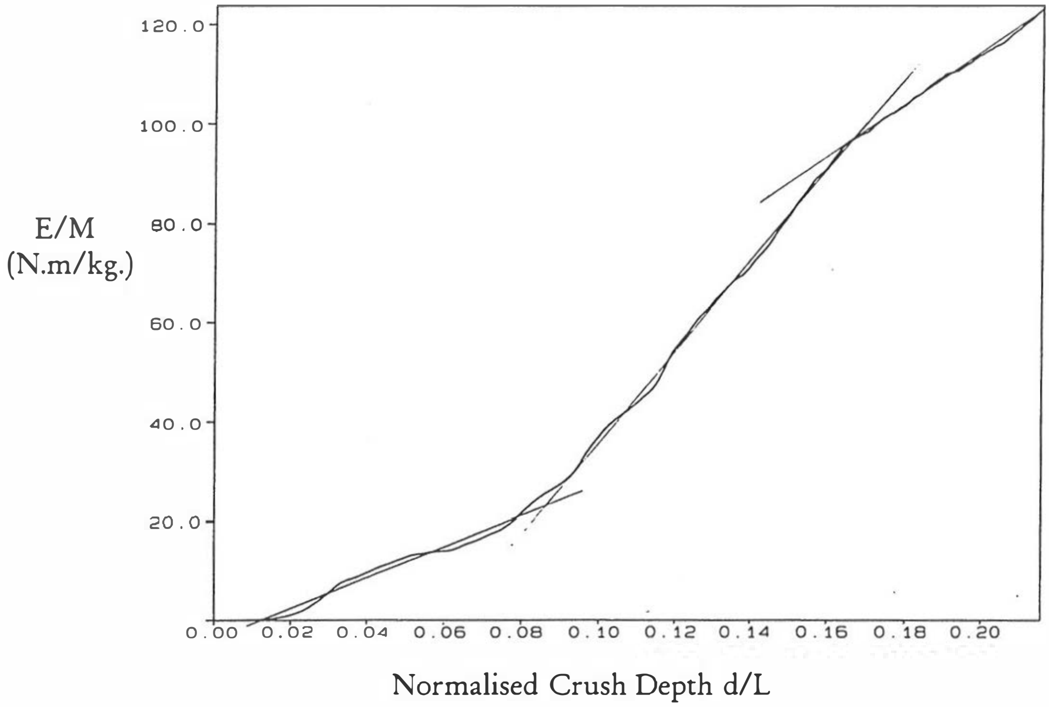


Figure 4 shows the cumulative energy absorbed by the car front in the full width barrier test as a function of crush depth, d/L. It shows that the crushing behaviour of this car in the full width barrier test has 3 distinct regions, each of which can be characterised in the figure by a straight line which corresponds to a constant force with a short transition between each. In each region the slopes of the respective lines represent the average force at which that portion of the car crushes. The first region, from a d/L value of 0.01 up to d/L of 0.087 has a low slope indicating a low force. The second region between 0.087 and 0.164 has a high slope while the third region, beyond d/L of 0.164, has a lower slope than region 2.

Comparison of the full width barrier characteristics of car 4 with its front structure shows that the peak force which occurs at a d/L of 0.03 corresponds with the location of the front longitudinal members and their initial buckling collapse. The end of the first region and start of region 2 at a crush depth, d/L, of 0.087 is 93% of the distance to the engine. The transition to the third region which occurs at a d/L of 0.164 is at 75% of the distance to the bulkhead/firewall between the car front and the occupant compartment, d/L of 0.218. Jones et al (1990) shows that the depth of crushed material behind the crush face of tubes is such that the distance to the crush face is, at most, 75% of the total distance to the rear of the crushed material. When the depth of the crushed materail immediately behind the crush face is taken into account and using the Jones et al (1990) 75% proportionality factor the transition point between regions 2 and 3 corresponds to the location of the fornt bulkhead/firewall. Region 3 continues up to the maximum dynamic crush at d/L of 0.216.

In the 45% overlap rigid barrier and the 30 degree angled barrier tests the maximum dynamic crush levels were 0.252 and 0.281 respectively. When the absorbed energy/dynamic displacement characteristics for these tests are examined both responses exhibit a 3 region constant force response similar to that of the full width barrier albeit with different average force levels and transition points. In terms of the straight line (constant force) approximations the transition points between each region are shown in Table 2 while the average force levels are detailed in Table 3.

Table 2 - Car 4 Constant Force Transition Points, d/L

Transition\Test	Full Width	45% Overlap	30 Degree
Region 1/2	0.087	0.096	0.174
Region 2/3	0.164	0.197	0.256

Table 3 - Car 4, Average Forces in each Region

Region\Test	Full Width	45% Overlap	30 Degree
	kN.	Percent Full Width Force	
1	67.4	57%	77%
2	204.2	68%	102%
3	117.8	62%	125%

For this particular car the average crushing forces in the 45% overlap rigid barrier test are all lower than in the full width barrier test while in the 30 degree angled barrier test only the first region force is lower than that of the full width barrier, the forces in regions 2 and 3 being similar but higher than those in the full width test. The essential difference between the full width and 30 degree angled barrier is that for the 30 degree angled barrier the onset of region 2, the highest force level, at a d/L of 0.174, is at twice the crush depth of the full width barrier at a d/L of 0.087. The crush depth interval $\{(d_{2/3} - d_{1/2})/L\}$ over which the high force region, Region 2, is maintained is essentially the same for both the full width $\{(d_{2/3} - d_{1/2})/L = 0.077\}$ and 30^0 angled barrier $\{(d_{2/3} - d_{1/2})/L = 0.082\}$ tests. In the 45% overlap test region 2 extends over a greater range of crush depth, $(d_{2/3} - d_{1/2})/L = 0.101$.

It is of particular interest to note that the bulkhead/firewall at the front of the occupant compartment is at a d/L of 0.218. Despite this the high, region 2, forces in the 30^0 angled barrier tests continues until a crush depth, d/L of 0.256 is reached, well after intrusion of the occupant compartment has started. This indicates that the changeover between the high forces in region 2 and the lower region 3 forces is not directly associated with the onset of intrusion of the occupant compartment but is a more complex function of the shape of the crush profile. This role of crush profile shape is confirmed by the 45% overlap test where the transition from region 2 to region 3 occurs at a crush depth, d/L of 0.197 (it occurs at d/L of 0.164 in the full width barrier test).

ALL CARS

In the full width barrier impact all the cars analyzed have an initial, region 1 crushing force which is followed by a higher second region force. All, with the exception of car 6, show a decrease in force before the maximum dynamic crush is reached. Four of the seven cars have a lower region 3 force for a sufficient crush distance to allow the average constant force for this region be determined. Table 4 shows the full width barrier region 2 constant force values for the cars and the region 1 and 3 constant force levels as a proportion of the region 2 values.

Table 4 - Full Width Barrier Constant Forces, kN.

Car	FORCE Region 2 kN.	FORCE 1/FORCE 2	FORCE 3/FORCE 2
1	227.3	43.6%	63.1%
2	187.1	48.7%	-
3	190.1	34.5%	-
4	204.2	33.0%	57.7%
5	519.2	15.5%	55.2%
6	294.1	85.3%	-
7	258.7	30.0%	43.6%
8	496.5	32.8%	-

The mean region 2 constant force is 297.2 kN. There is a high variability in the force level between the eight cars from a minimum of 187.1 kN. to a maximum of 519.2 kN.

With the exception of car 6 which has a high region 1 force at 85.3% of the region 2 level, the other seven cars have low region 1 forces levels which average 34% of their region 2 forces. For the four cars where the region 3 constant force level could be determined it averaged 55% (54.9) of the corresponding region 2 force.

Figures 5 to 7 show the averaged responses for all 8 cars in the full width, 45% overlap and 30 degree angled barrier tests. Comparison of the force levels in each stage for the 45% overlap and the 30 degree angled barrier with the corresponding full width barrier values are shown in Table 5.

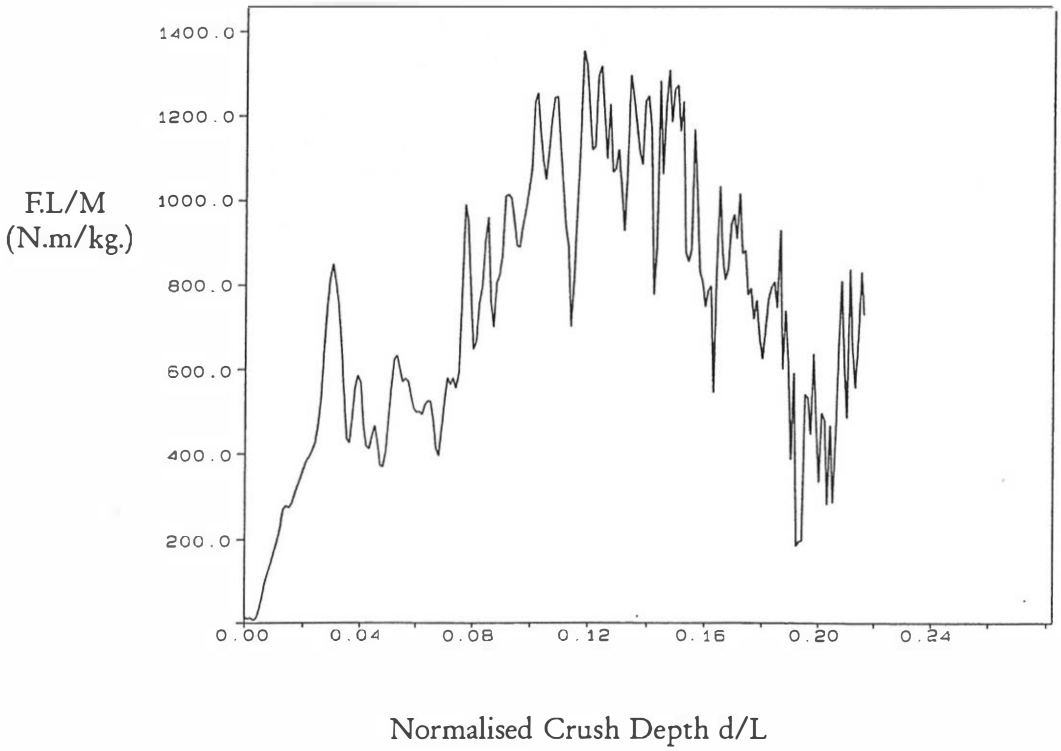
Table 5 - All Cars, 45% Overlap & 30 degree Forces compared to the Full Width Forces

Region\Test	45% Overlap	30 Degree
Region 1/Region 1 F.W.	60.9%	53.6%
Region 2/Region 2 F.W.	78.0%	100.0%
Region 3/Region 3 F.W.	55.3%	95.2%

Table 5 shows for all cars that the force levels in the 45% overlap tests are lower than in the full width barrier tests whereas the regions 2 and 3 force levels in the 30 degree angled barrier tests are similar to those obtained in the full width tests.

Statistical analysis for all 8 cars shows that position of the initial force peak corresponds with the location of the front of the longitudinal members and that the transition points between regions 1 and 2 in the full width barrier tests are, on average, at 75% of the distance to the front of the engine and that the onset of the force decrease at the end of stage 2 in the full width and 45% overlap tests is at 75% of the distance to the bulkhead/firewall. This 75% proportionality corresponds to the depth taken up by the crushed material behind the crush face shown by Jones et al (1990) in the crushing of tubes.

Figure 5. Average Full Width Response - All Cars.



One explanation for the absence of a region 3 for car 6 is that the crushing was not sufficient to reach this region and involve the occupant compartment in the crushing process. The maximum crush in the full width test was 58% of the distance to the bulkhead/firewall while it was 69% in the 45% overlap test, i.e. both are less than the 75% crush face/crush depth ratio from Jones et al (1990) necessary for the crushed material to reach the front bulkhead/firewall.

COMMENT

Examination of the full width crushing of car fronts in relation to their crush depths shows that sequentially there is an initial low average force typically 34% associated with crushing of the longitudinal struts. This is followed by a higher force (100%) associated with the crushing of the engine and the rear front structure followed in turn by a lower, typically 55% force which is associated with the crushing of the occupant compartment. The fact that a lower crushing force associated with crushing of the occupant compartment follows the higher forces imposed during crushing of the engine compartment has been shown by Johnson et al (1978) to be due to dynamic inertial effects.

Figure 6. Average 45% Overlap Response - All Cars.

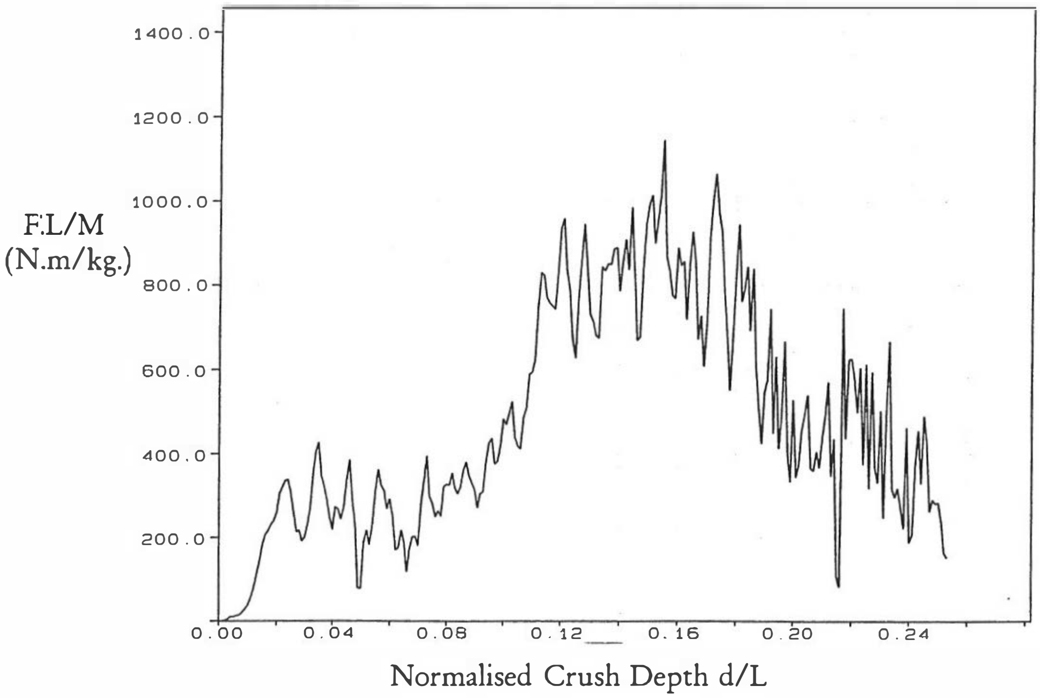
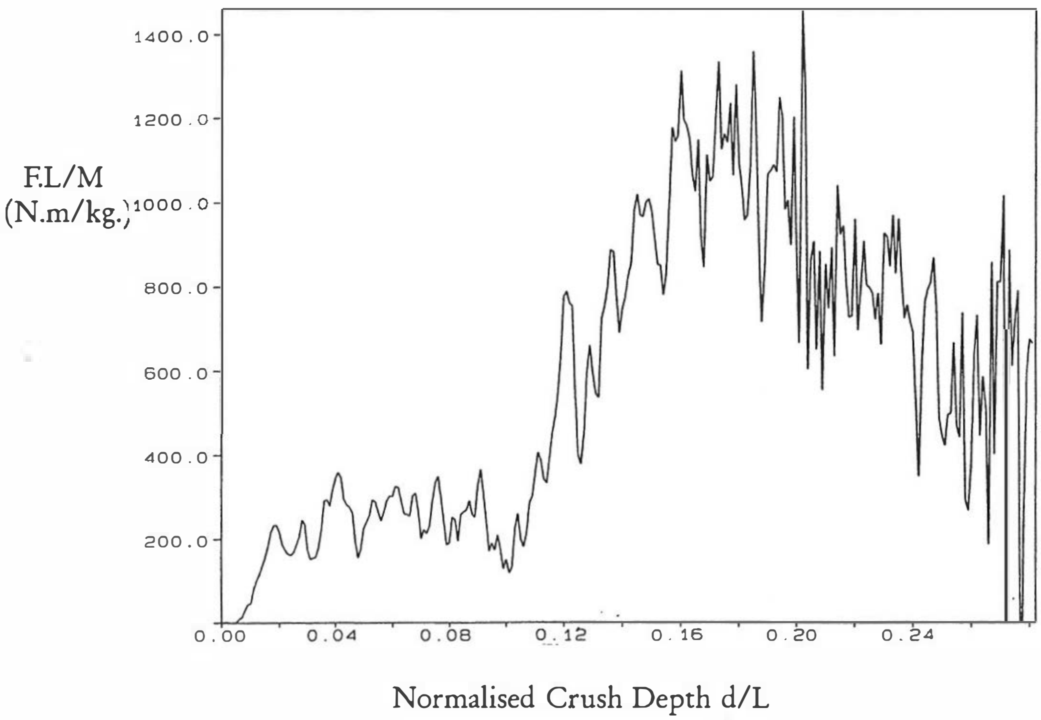


Figure 7. Average 30° Angled Barrier Response - All Cars.



The tests show that in the 45% overlap tests the force levels in all regions are lower than in the full width tests. In the 30 degree angled barrier tests the region 2 and 3 force levels are similar to those in the full width tests the main difference between the 30 degree and full width responses being the lower forces in the 30 degree test during initial crushing and the Larger depth of crush before the onset of the region 2 and 3 forces in the 30 degree barrier tests. For the full width barrier tests the transition points between the 3 constant force regions when adjusted for the crushed depth of material match with the front of the longitudinal, the front of the engine cum rear front structure and with the bulkhead/firewall at the front of the occupant compartment.

The results also show that the crush depths over which the three force regions take place depend on the shape of the crush profile with regions 2 and 3 occurring at the smallest crush depths in the full width flat barrier tests and the greatest depths of crush before the onset of these force regions in the 30^0 degree angled barrier tests.

The large variation particularly in the region 2 force levels from 187.1 kN. to 519.2 kN. has considerable implications for compatibility between cars. In car to car collisions the distribution of crush depths between the collision pair will depend on the force/depth crush behaviour of both cars and on the inertial forces of the deforming structures, Wood (1996). The force balance at the interface between the two cars, particularly in region 2, will largely be determined by the weaker car which will then have the preponderance of crushing. As the data indicates that the region 3 force levels are lower than those of region 2, if the collision severity is sufficiently high the crushing of the weaker car will continue into the occupant compartment while the second car only experiences low crushing. Tarriere et al (1994) have examined this behaviour. More equal sharing of the crush between cars can only be achieved by regulating the average crushing force in region 2 in the full width barrier test to within a specified range for all cars. Also consideration should be given in smaller cars of making the crush strength of the occupant compartment greater than that of the rear front structure and thereby ensuring that the collision partner preferentially deforms once the crushing of the smaller car has reached the front bulkhead/firewall.

The smaller crush depths for car 6 are associated with the higher region 1 force (85.3%) for this car in comparison with the other seven cars which had an average region 1 force of 34%. This approach is one way of reducing crush depth and delaying the onset of occupant compartment intrusion, however care is needed to avoid increasing injury in the large number of lower speed impacts due to the increased initial crushing forces. The analysis also shows that there is the potential to increase the structural strength of the occupant compartment and thereby reduce the effects of intrusion.

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