ROZPRAWY INŻYNIERSKIE • ENGINEERING TRANSACTIONS • 29, 1, 83—97, 1981
Polska Akademia Nauk • Instytut Podstawowych Problemów Techniki

DYNAMIC PLASTIC ENERGY ABSORPTION IN VEHICLE IMPACT

N. PERRONE (ARLINGTON)

Simplified as well as comprehensive dynamic plastic mathematical models of vehicle structures can and do play a very useful role for the purpose of assessing energy absorption potential for vehicle or highway structures during impact. A number of success stories are evident within the vehicle itself in the windshield, door latches, and steering columns as well as overall vehicle crush capability. In the highway environment the advent of energy absorbing barrier systems, breakaway sign posts, and effective bridge rail systems have contributed noticeably to improved safety on the highway. The awareness by the design community of the effectiveness of improved energy absorption has resulted in improved vehicle safety. With no standard existing or contemplated in the U.S. for vehicle energy absorption, this capability is left largely up to the discretion of the manufacturer. Selective increments in vehicle component energy absorption are feasible (front, rear, side, interior) via static tests with rate sensitivity correction factors and also possibly the use of lumped mass models. The need for energy absorption is tempered with the challenge of decreasing weight of vehicles because of energy saving requirements. This difficulty challenges the ingenuity of the designer but there is likely still much room for improvements when we consider that the specific energy absorption for various configurations can be made quite high [1]. A complicated problem with the Unites States in recent years has been the big car—small car mix. During impacts between vehicles of grossly different weight the smaller car obviously suffers heavily. This transition period makes it even more imperative, to have good impact absorbing capabilities within the very light and small vehicle. In addition, a trend also exists toward lighter weight materials such as the use of composites (which are under study). The energy absorption of these materials must be examined very closely because they frequently would not be as ductile as metals which they are trying to replace. Rate sensitivity for these newer materials are may also still be a problem. The challenge of packaging people in vehicles to survive impact events, not consume too much energy, and still provide the function of reasonable transportation is indeed formidable and is being met very capably by the mechanics, materials, and engineering communities.

1. INTRODUCTION

The essential problem in vehicle impact is to absorb kinetic energy in a controlled and efficient manner. This control relates to biodynamical as well as structural response subsequent to an impact. It may be instructive to examine in Fig. 1 a range of kinetic energy which must be absorbed by a body component or vehicle area during impact. Obviously, for the vehicle itself, controlled energy absorption in the range of 20.000 to 160.000 foot pounds is necessary. A fundamental principale in this process is that the passenger volume is intruded upon to the slightest extent possible during the impact event to maximize probability of survival of occupants.

Of course, designing for controlled energy absorption must be done in parallel with the vehicle's primary function, namely to transport occupants efficiently.

Obviously, the vehicle must have a propulsion unit, lights, windows, etc. and also should be light enough to be energy efficient.

Despite these difficult constraints, it should be feasible with judicious design to incorporate energy absorbing potential in the vehicle for the range described in Fig. 1. As has been pointed out previously [1], the amount of material by weight necessary to absorb 500 foot pounds of energy is approximately 1 pound. (Actually, with sophisticated energy absorbing concepts many thousands of foot pounds of energy can be absorbed for each pound of energy absorbing material). Therefore, vehicle weight necessary to absorb say 60.000 foot pounds of energy is about 120 pounds. When we consider that the structure doing the energy absorption will also be simultaneously carrying out other functions such as supporting the engine, minimizing vibrational response, and general structural integrity, the weights necessary for controlled energy absorption are well within feasible limits.

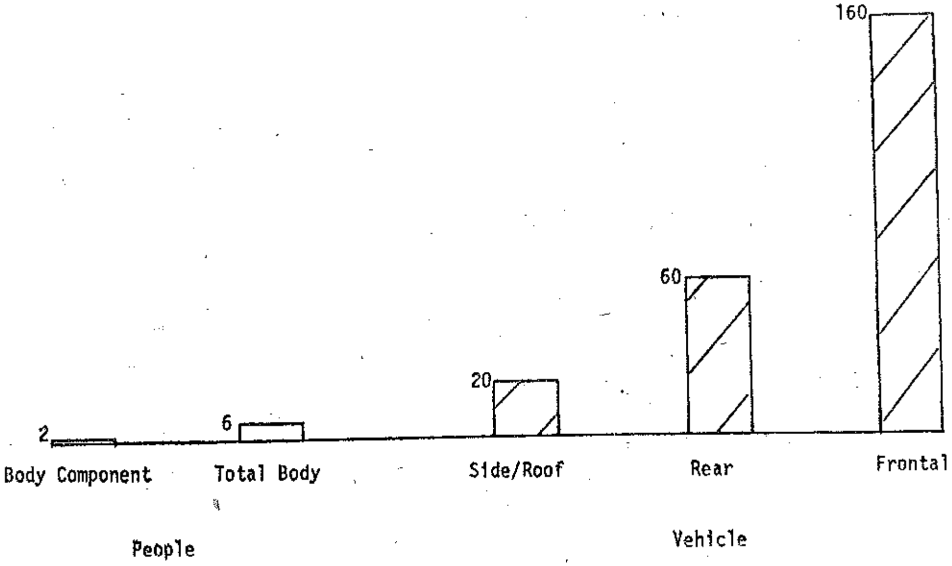

FIG. 1. Energy absorbing range (in K Ft.-Lbs.) for vehicle impact.

Some of the complications attendant with controlled energy absorption in vehicle impact include: a) rate sensitivity effects which occur in a first order way for the type of steels normally used in vehicle structures. These effects can greatly enhance the energy absorbing potential of the crushing structure. b) The complicated collapse pattern which a vehicle normally crushes. This result makes it difficult to determine the energy absorption in a fully predictive manner.

In the next section, methods of determining and improving the energy absorption of vehicles are discussed utilizing basic dynamic analysis principles. The subsequent section describes a number of successful energy absorption design attempts for the vehicle or highway environment. The last section concludes with a summary and discussion of trends.

2. IMPROVING VEHICLE ENERGY ABSORPTION FROM BASIC PRINCIPLES

As mentioned earlier, the problem of plastic rate sensitivity for vehicle structural steels is a significant one and should be included in the analysis and design. A number of papers addressing this subject area are suggesting methods by means of which these effects can be rationally incorporated into analyses [2–7]. The simplest such approach would be to take static force deflection crush data for a vehicle component (front, rear, or side) and include an appropriate rate sensitivity correction factor in the range of 1.3 to 1.6. Verification of these factors can be achieved by correlating with a small number of full scale tests.

One purpose of front seat backs is to provide restraint to occupants during rear impacts. In view of the fact that the seat back can be modelled as a cantilever beam, it should be possible to design the strength of this beam associated with a minimal level of yield moment for realistic full scale problems, say 100.000 inch-pounds [8–9]. This level should include rate sensitivity effects.

The energy to be absorbed in the frontal and rear areas of a vehicle could be determined using the static crush tests as described above. By placing the entire vehicle in a vice-like structure and monitoring the force deflection response during a very slow crush process, one could determine important response parameters for the vehicle. The associated dynamic response characteristics could be determined again with an overall rate sensitivity factor.

Side impact is perhaps more dangerous on balance than frontal or rear in that little crush space is permitted before serious intrusion occurs into vehicle occupant space. When impact occurs in the door area, the latch system is the primary mechanism to prevent door intrusion. Enhanced membrane action should be feasible by a tongue and groove design along the entire periphery of the door region.

Lumped mass models have also been used to determine the dynamic plastic response of an entire vehicle system. The static crush data for individual components can be utilized with a rate sensitivity correction factor to determine vehicle response. Indeed such models which have been devised form a semi-empirical viewpoint have proven to be fairly representative of actual vehicle response [10].

3. SOME SUCCESSFUL ENERGY ABSORPTION VEHICLE/HIGWAY PROGRAMS

In the previous section a number of concepts are discussed to enhance or understand better the concept of energy absorption in a vehicle impact situation. In the present section specific example areas are discussed wherein a very successful and operational capability has been developed for the vehicle system itself or an element in the highway environment.

It has bee well known for many years that vehicles do, for one reason or another, wander off highways and impact barriers along the road be they sign posts, poles, bridge abutments, bridge rail systems, or gore area concrete barriers, [11–13]. These impacts are frequently very traumatic as shown by the photo of Fig. 2. The

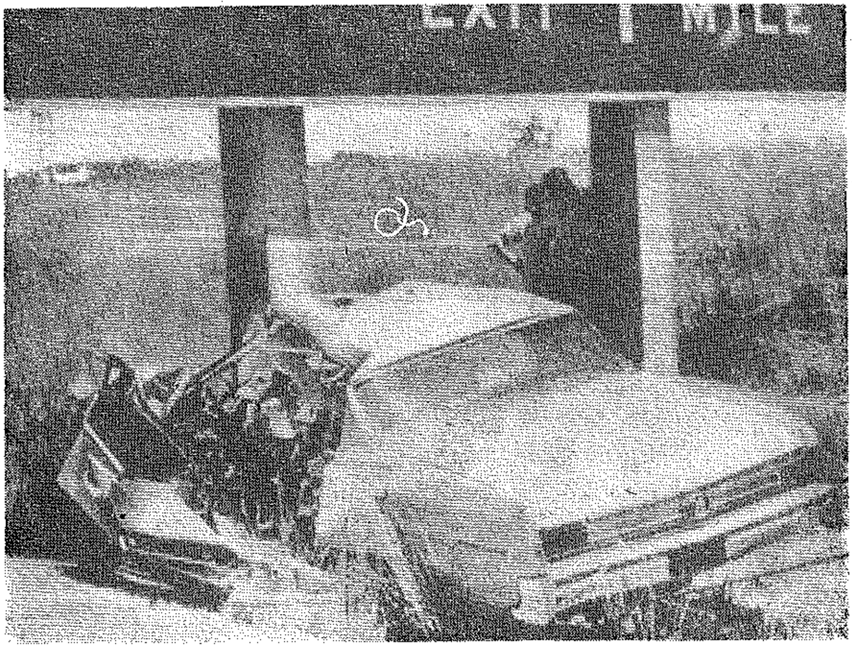

FIG. 2. Fatality accident due to impact with rigid sign post.

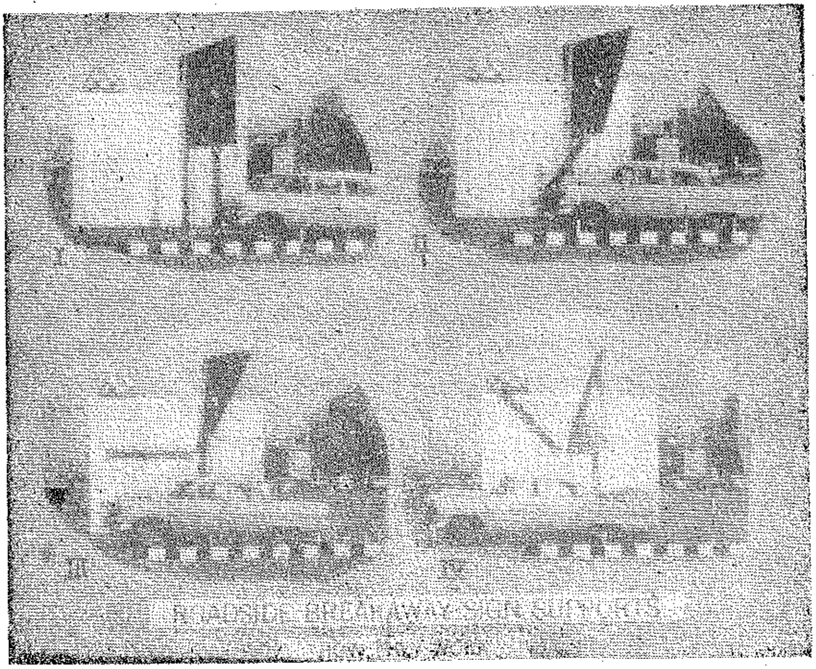

FIG. 3. Break away sign impact sequence.

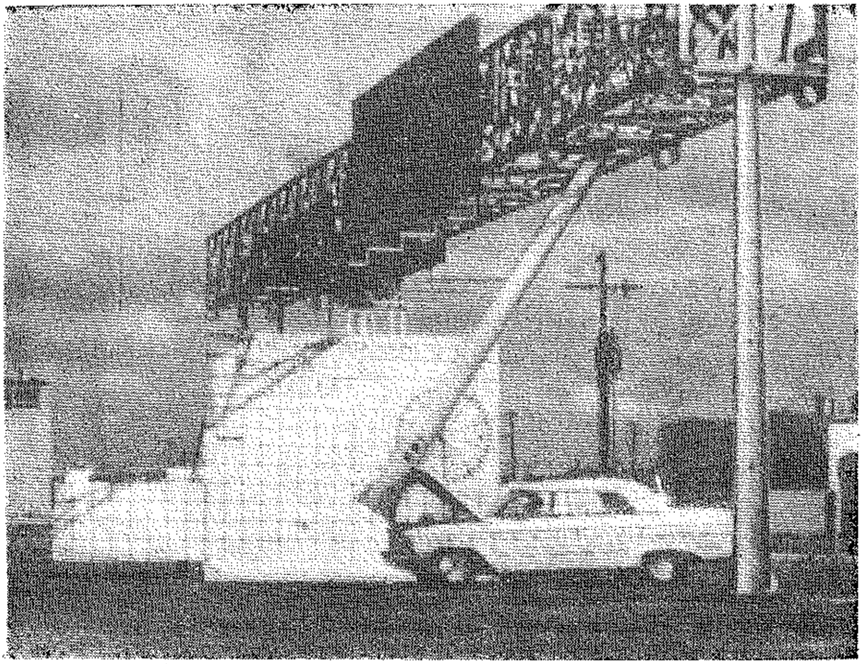

FIG. 4. Full size car impacting break away sign simulation.

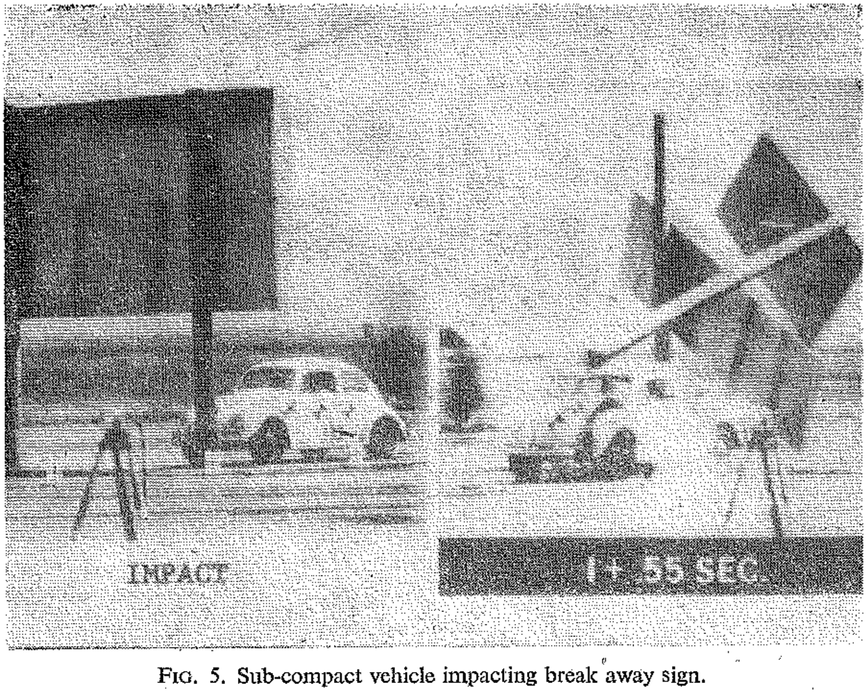

FIG. 5. Sub-compact vehicle impacting break away sign.

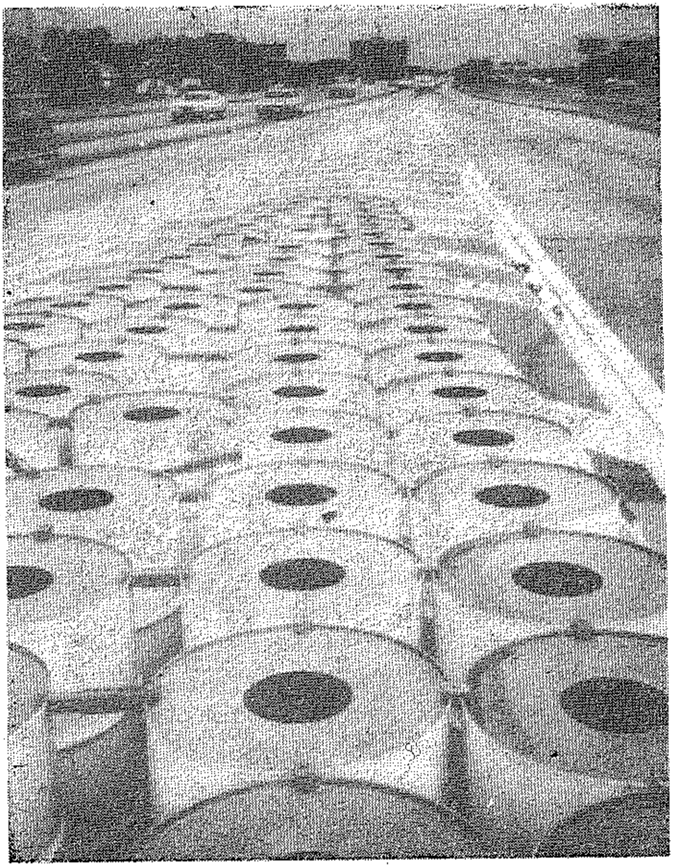

FIG. 6. View from gore area towards road overlooking steel barrel barrier.

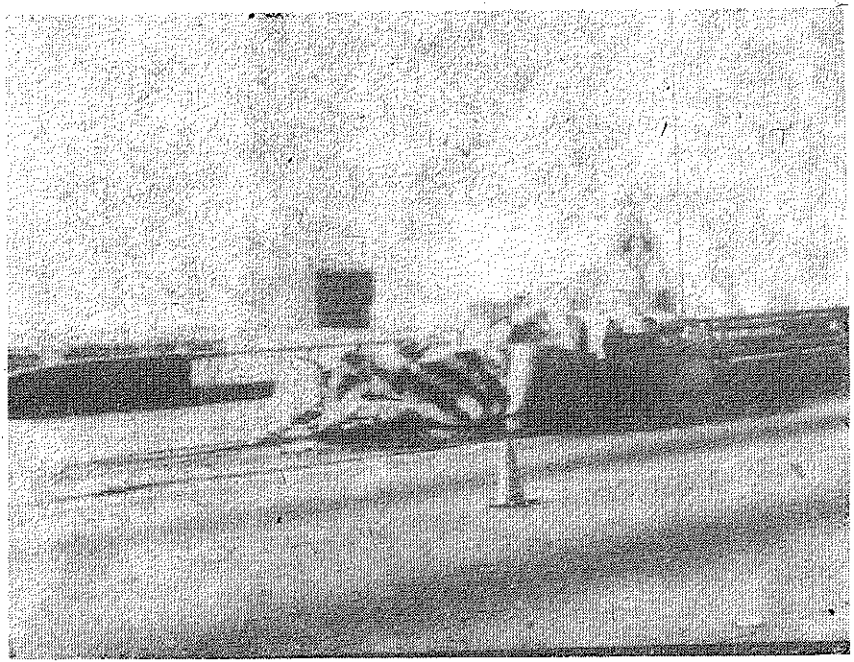

FIG. 7. Steel barrel barrier after actual accidental impact at 70 M.P.H.

FIG. 8. Minimal vehicle damage in highspeed impact with steel barrel barrier.

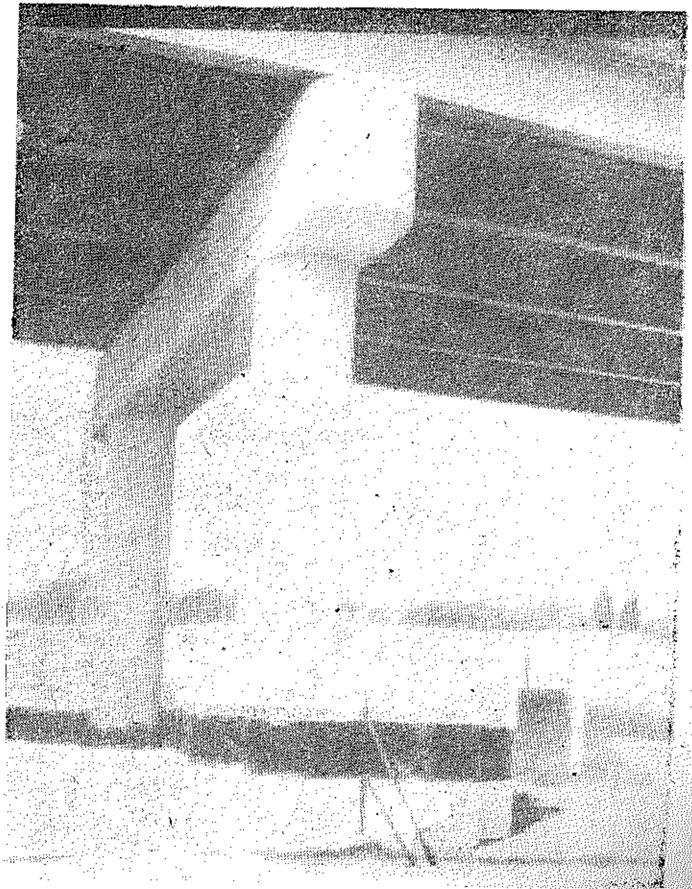

FIG. 9. Steel barrel system protecting bridge abutment.

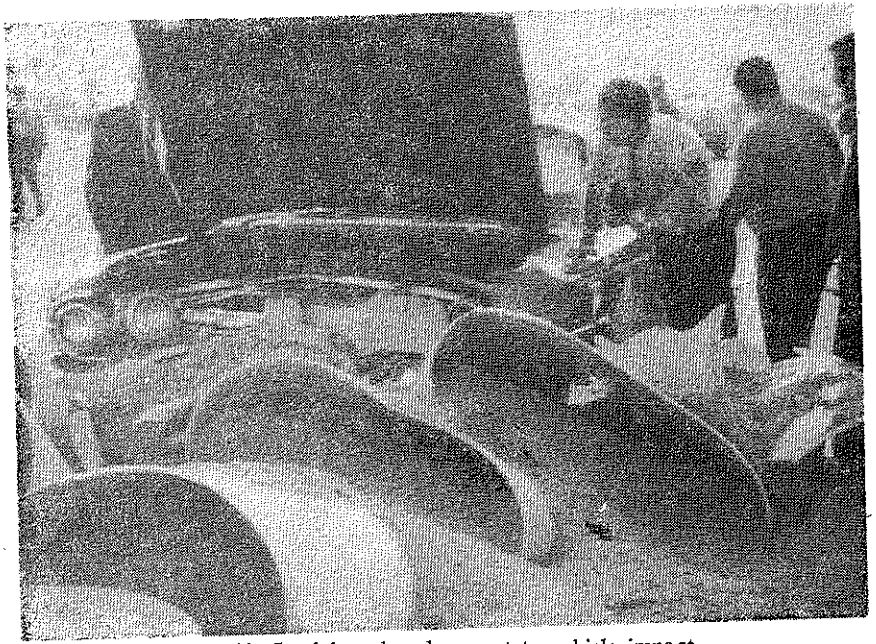

FIG. 10. Sand barrels subsequent to vehicle impact.

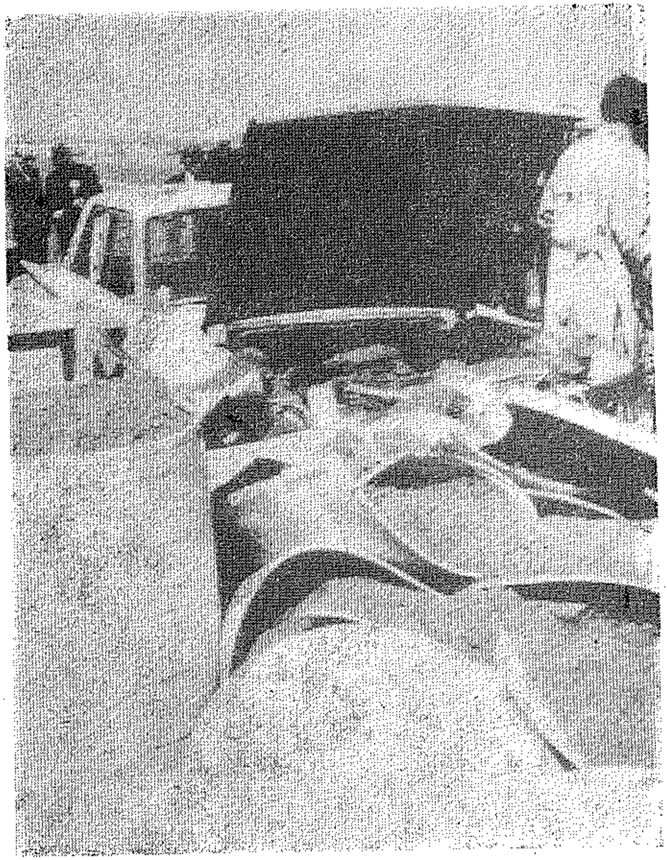

FIG. 11. Another view of sand barrel system after vehicle impact.

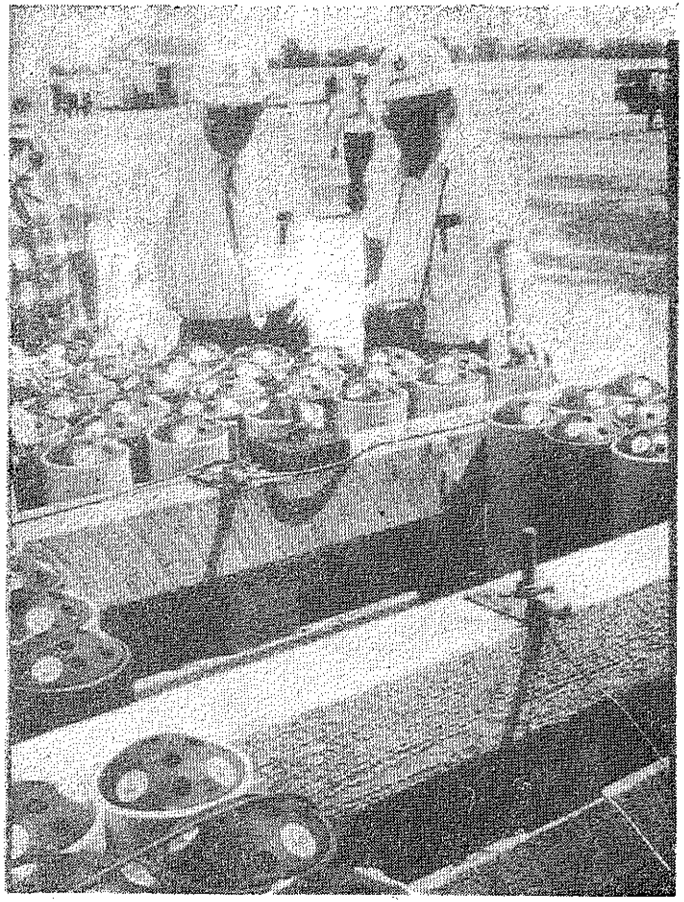

FIG. 12. Hydrocell system array with view of upper section.

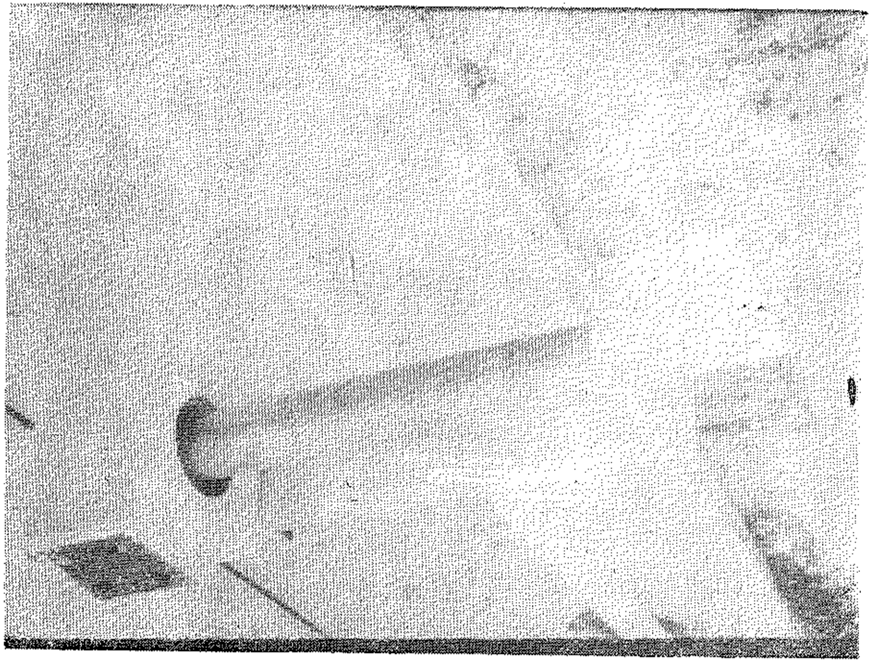

FIG. 13. Frangible tube standoff for bridge rail system.

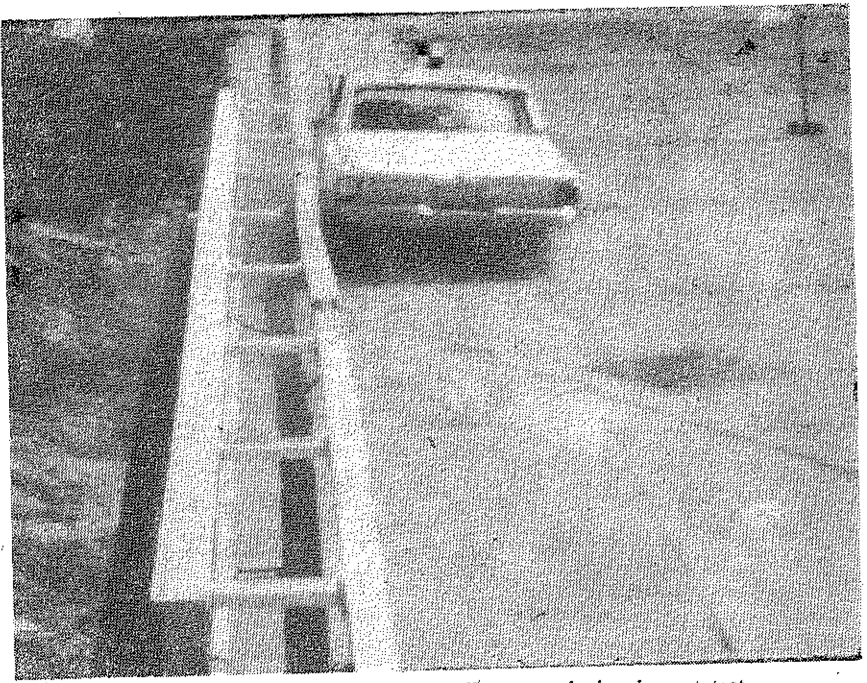

FIG. 14. Frangible tube bridge rail system during impact test

FIG. 15. Thick walled ring energy absorbing bridge rail system.

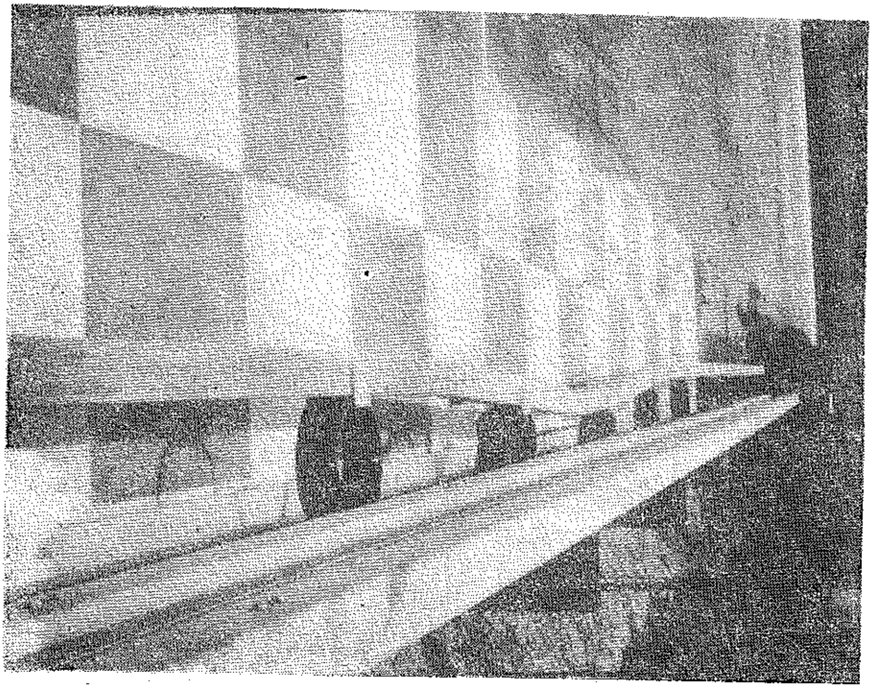

FIG. 16. Ring bridge rail system after test.

FIG. 17. Modified tubular bridge rail system after full scale test.

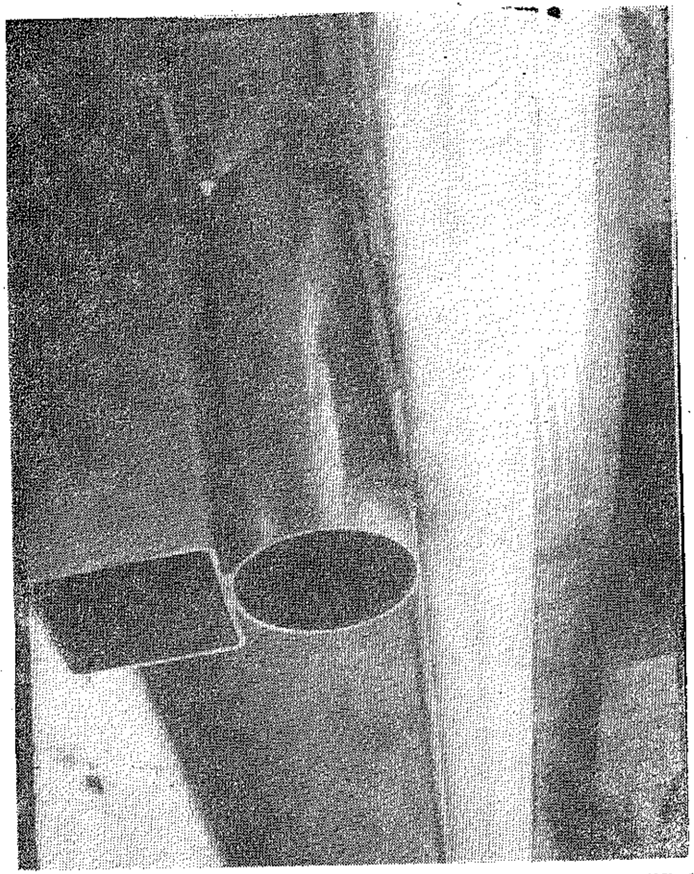

FIG. 18. Close-up of energy absorbing tube element in modified bridge rail system.

FIG. 19. Close-up of crushed tube element after test.

normally high highway speed impact against a rigid off road structure is understandably traumatic. Clearly, the kinetic energy of the vehicle in Fig. 2 is translated into violent vehicle plastic deformations and significant intrusions into the passenger compartment. By contrast, breakaway sign posts have proven in full-scale tests to be extremely effective as shown in the series of photographs of tests in Figs. 3–5. What obviously has occurred from these illustrations is that only a small portion of the vehicle kinetic energy is dissipated in causing the breakaway of the sign; vehicle occupants could survive such an event with modest or virtually no injury [14].

At a so-called gore area, that is the zone between the main highway and the turn off, there normally exists a rigid and dangerous impact area. A view towards the highway from the rigid area is shown in Fig. 6. The assembly of empty steel barrels fastened together is an energy absorbing (*EA*) system which has proved to be extremely effective [15]. Accidents have occurred at speeds up to 70 miles per hour into such barrier systems in which occupants have survived with modest injuries. A photo of an actual barrier is shown in Fig. 7 subsequent to such a high speed impact.

In controlled tests against steel barrel (*EA*) devices one can see the relatively little amount of energy absorbed by the vehicle versus the barrel structure, Fig. 8. These steel (*EA*) devices have also been used to protect vehicle occupants from impact with bridge abutments, Fig. 9.

Other cheaper systems which have been used with increased frequency within the United States include sand filled barrels which also have the effect of absorbing vehicle kinetic energy in a very desirable manner. Photos of some full scale tests shown in Figs. 10 and 11, and again the relative modest level of vehicle damage is apparent. Still another form of energy absorbing systems which is especially useful where a large crush distance is not available is the so-called hydrocell system consisting of water filled rubber, cylinders with caps which open upon impact, Fig. 12. The vehicles kinetic energy is therefore transformed into moving a large mass of water upward.

Both a guard rail and a bridge rail have the purpose of redirecting a vehicle heading off a highway back towards the roadway. A much higher premium is placed on the bridge rail system, which should not be penetrated. Energy absorbing bridge rail systems have been attempted using a frangible tube as the *EA* device [16]. A picture of the device itself along with a full scale vehicle test is shown in Figs. 13 and 14. While these devices were useful, they were not practical for installation in an actual highway environment. With Federal Highway Administration support an effort was successfully completed to replace the frangible tube *EA* element by a deforming ring which also acted as the cantilever agent for the box-beam rail [17]. Rate sensitivity effects were also included in the formulas which were derived which could apply to any crush in tubular structure [17]. Ring bridge rail systems were built and tested as shown in Figs. 15 and 16 and have been installed in a number of sites in the United States. The formulas derived in [17] accounting for tube crush with plastic rate sensitivity and strain hardening have also been used for other energy absorbing bridge rail systems as shown in Figs. 17–19.

Other success stories relating to energy absorbing systems within the vehicle itself include impact resistent door latches, windshields which absorb head and upper torso kinetic energy up to 30 miles per hour and energy absorbing steering columns. The essential and final point is that controlled energy absorption works if properly implemented within the vehicle itself or the associated highway environment. Despite the complications of rate sensitivity, large deformations, failure to collapse in a fully predictive manner and the like, the technology of controlled energy absorption remains a useful option for the vehicle impact problem.

REFERENCES

1. N. PERRONE, *Crashworthiness and biomechanics of vehicle impact*, Special ASME Publication Dynamic Response of Biomechanical Systems, American Society of Mechanical Engineers, December 1970.
2. W. BAKER, *Approximate techniques for plastic deformation of structures under impulsive loads*, Shock and Vibration Digest, 7, 7, 1975.
3. N. JONES, *A literature view of the dynamic plastic response of structures*, Shock and Vibration Digest, 7, 8, October 1978.
4. N. PERRONE, *On a simplified method for solving impulsively loaded structures of rate senstiive materials*, ASME J. of Appl. Mech., September 1965.
5. N. JONES and T. WIERZBICKI, *A study of the higher modal dynamic plastic response of beams*, Intern. J. of Mech. Sci., **18**, 1976.
6. R. C. SHIEH, *Strain rate sensitivity effects on crash response and dynamic yield formulas for crash prediction of automobile bumpers*, Proceedings 16th Structures Structural Dynamic and Materials Conference, AIAA, 1975.
7. N. PERRONE and P. BHADRA, *A simplified method to account for plastic rate sensitivity with large deformations*, J. of Appl. Mech., December 1979.
8. N. PERRONE, *A position paper on vehicle safety*, Catholic University of America Technical Report, September 1970.
9. P. S. SYMONDS and J. JONES, *Impulsive loading of fully clamped beams with finite plastic deflection and strain rate sensitivity*, Intern. J. of Mech. Sci., **14**, 1972.
10. J. E. TOMASSONI, *A study of the effect of strain rate on the automobile crash dynamic response.* Proceedings of the AIAA/ASME 19th Structures. Structural Dynamic and Materials Conference. 1978.
11. F. J. TAMANINI and J. G. VINER, *Structural systems in support of highway safety*, Preprint No. 930 ASCE National Meeting on Transportation Engineering Washington D. C., July 1969.
12. *Highway Research Board*, Highay Research Record No. 343, Design of Traffic Safety Barriers. 1971.
13. F. J. TAMANINI and J. G. VINER, *Energy absorbing roadside crash barriers*, Civ. Engineer., January 1970
14. *Highway Research Board*, Highway Research Record No 346, Design of Sign Supports and Structures, 1971
15. T. J. HIRSCH and D. L. IVEY, *Vehicle impact attenuation by modular crash cushion*, Texas Transportation Institute Report, 146-1, College station, Texas, June 1969
16. T. J. HIRSCH, A. J. STOCKER, D. L. IVEY, *Energy absorbing bridge rail (fragmental tube)*, Annual Meeting of highway Research Board, Washington, D. C., January 1970
17. N. PERRONE, *Thick walled rings for energy absorbing bridge rail systems*, Federal Highway Administration Report, December 1972.

STRESZCZENIE

POCHŁANIANIE ENERGII PRZEZ PLASTYCZNE DEFORMACJE W ZDERZENIACH SAMOCHODÓW

Uproszczone modele obliczeniowe plastycznego zachowania się konstrukcji w zakresie obciążeń dynamicznych są bardzo przydatne w określaniu możliwości pochłaniania energii elementów pojazdów lub przeszkody w czasie zderzeń. W zakresie tym widoczny jest znaczny postęp głównie jeśli chodzi o konstrukcję bezpiecznych szyb, zamków drzwi, kierownicy i kontrolowanej odkształcalności przodu samochodu. Jeśli chodzi o inżynierię budowy dróg, to bezpieczeństwo jazdy podniesione zostało poprzez wprowadzenie systemu barier pochłaniających energię, łamliwych lub odkształcalnych słupów i znaków drogowych oraz belek ochronnych na mostach i wiaduktach.

Dalszy postęp w projektowaniu enrgochłonnych elementów konstrukcyjnych pojazdów możliwy jest poprzez wprowadzanie statycznych prób zgniatania, uwzględnienie wpływu prędkości odkształcenia oraz opracowania programu symulacji zderzeń za pomocą metody dyskretyzacji na skupione masy i nieliniowe sprężyny. Projektowanie konstrukcji efektywnie pochłaniających energię jest dodatkowo utrudnione wymaganiami zmniejszenia ciężaru pojazdów oraz ich elementów w dobie kryzysu energetycznego. Ponadto występowanie na drogach pojazdów o zróżnicowanym ciężarze utrudnia wypracowanie jednolitych kryteriów bezpieczeństwa przy zderzeniu. Wszystkie te nie rozwiązane problemy stwarzają olbrzymie możliwości stosowania metod nieliniowej mechaniki konstrukcji.

Резюме

ПОГЛОЩЕНИЕ ЭНЕРГИИ ПЛАСТИЧЕСКИМИ ДЕФОРМАЦИЯМИ В СТОЛКНОВЕНИЯХ АВТОМОБИЛЕЙ

Упрощенные расчетные модели пластического поведения конструкции в интервале динамических нагрузок очень пригодны для определения возможности поглощения энергии элементов автомобилей или преграды во время столкновений. В этой области наблюдается значительный прогресс главным образом если имеется в виду конструкции безопасных стекол, замков дверей, руля и контролируемой деформируемости передней части автомобиля. Если имеется в виду инженерное дело строительства дорог, тогда безопасность езды повышается путем введения системы барьеров поглощающих энергию, ломких или деформируемых столбов и дорожных знаков, а также защитных балок на мостах и эстакадах. Дальнейший прогресс в проектировании конструкционных элементов автомобилей поглощающих энергию возможен путем введения статических сдавливающих испытаний, учета влияния скорости деформации, а также разработки программы имитации столкновений при помощи метода дискретизации на сосредоточенные массы и нелинейные пружины. Проектирование конструкции эффективно поглощающих энергию дополнительно затруднено требованиями уменьшения веса автомобилей и их элементов в период энергетического кризиса. Кроме этого выступание на дорогах автомобилей с разным весом затрудняет разработку однородных критериев безопасности при столкновении. Все эти нерешенные проблемы создают возможности применения методов нелинейной механики конструкций.

OFFICE OF NAVAL RESEARCH, ARLINGTON, VIRGINIA, USA

Received May, 1980.