ROZPRAWY INŻYNIERSKIE · ENGINEERING TRANSACTIONS •29, 1, 51—68, 1981
Polska Akademia Nauk • Instytut Podstawowych Problemów Techniki

AN EXPERIMENTAL STUDY OF PLASTIC HINGES AND JOINTS IN THIN-WALLED TUBES

M. MATOLCSY (BUDAPEST)

The paper discusses various modes of plastic failure of thin-walled prismatic tubes subjected to comparison and/or bending with particular application to the design of safe bus underframe and superstructure. For compressed tubes a critical length was determined experimentally separating regions of local and global loss of stability. For members subjected to bending, an empirical relation was proposed describing the relationship between the bending moment and the rotation angle at a hinge. The behaviour of tubular joints under combined compression and bending was also studied. The effect of imprefection was taken into account by introducing in the description of hinge characteristics the probability distribution functions.

1. INTRODUCTION

In the course of extensive investigations over the past few years the main passive safety requirements of buses have been formulated. One group of these requirements concerns the structural integrity of the framework in the case of an accident so that sufficient survival space is retained for the passengers and the driver. The design can meet this requirement if the energy absorption characteristics and strength criteria of structural members subjected to large plastic deformations are well understood. The bus frame structure is built up of thin-walled rectangular tubes. This production method of bus bodies is widely used throughout the world and, in particular, in Hungary.

The paper is devoted to an experimental study of strength characteristics and energy absorption capacity of several types of plastic hinges and joints.

2. GENERAL PROPERTIES OF PLASTIC JOINTS

The generalized plastic hinge is understood as a relatively small portion of a thin-walled tube in which local loss of stability in the plastic range takes place leading to a severe distortion of a structure as a whole.

Three typical types of plastic joints can be distinguished: 1) joints characterized by the compressive force F and shortening s, (Figs. 1a–1c); 2) joints characterized by bending moment M and angular displacement (Fig. 1d); 3) combined joints (Fig. 1e).

Theoretically one can define joints with limited or unlimited deformation. In real bus structures which were involved in a collision as well as in our tests the formation of all these types of joints was observed.

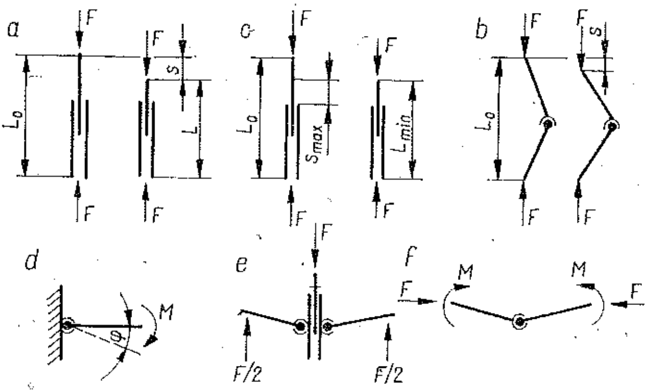

FIG. 1. Types of plastic hinges.

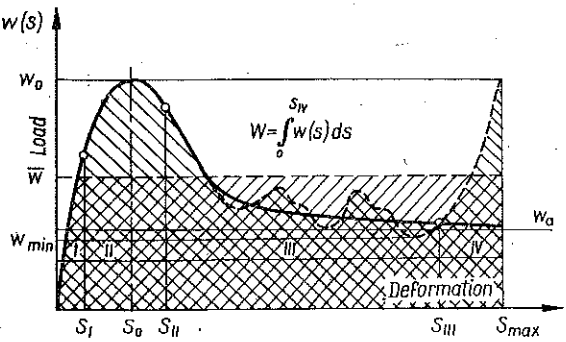

FIG. 2. Joint characteristics.

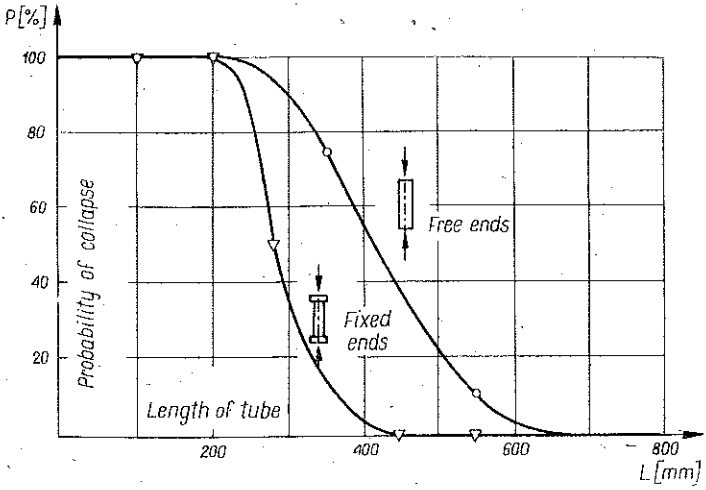

FIG.3.Collapse probability of compressed tubes.

A typical load deformation curve $w = w(s)$ of the plastic joint is shown in Fig. 2. Initially the structural response is elastic but usually nonlinear. Then there follows an elastic-plastic range in which loss of stability is observed at a certain deflection s_0. The maximum load $w(s_0)$ corresponding to the loss of stability is called the initiation of plastic hinge. In the post-buckling range $s > s_0$, the load drops until the opposite sides of the cross-section are joined and the hardening process takes place. In the case when one or several folds are formed during the crushing process, the folding wave in the force diagram is superimposed on the basic function.

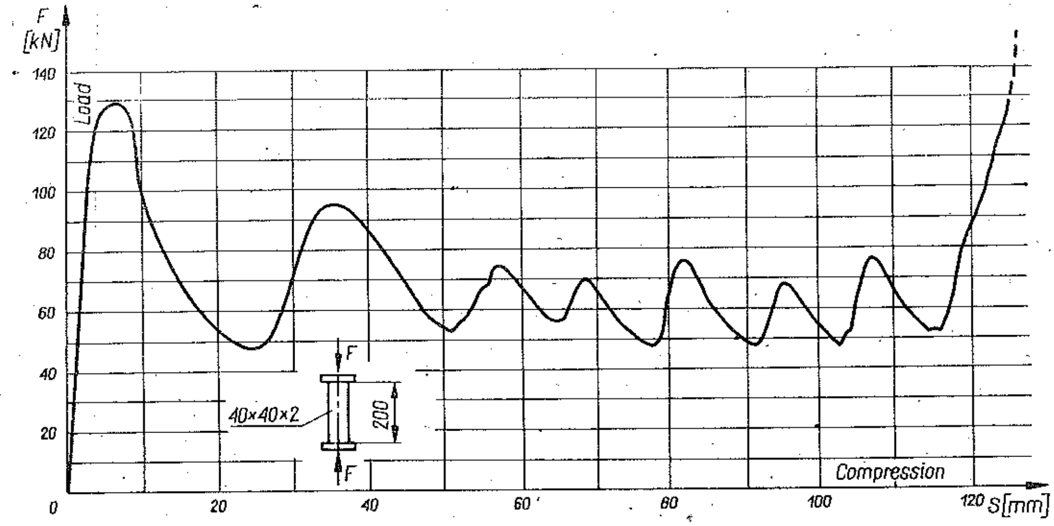

FIG. 4. Hinge characteristics of folding type plastic hinge.

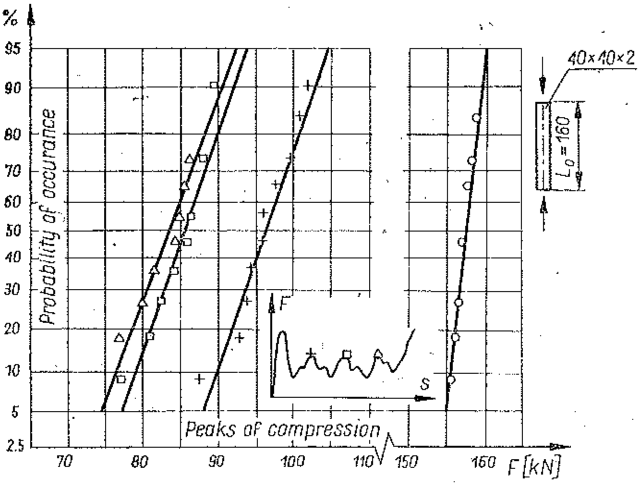

FIG. 5. Distribution functions of load maxima.

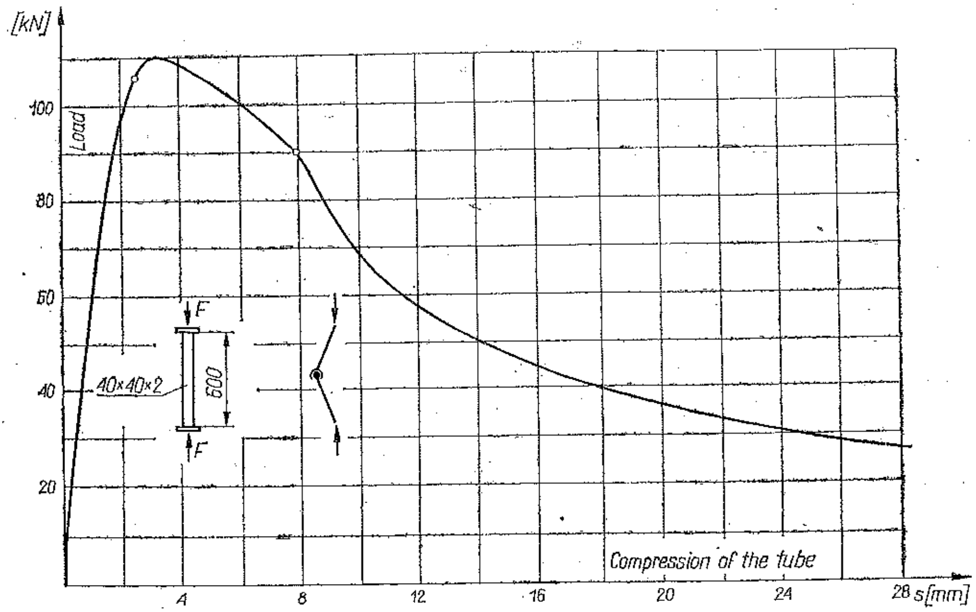

FIG. 6. Characteristics of local buckling type plastic hinge

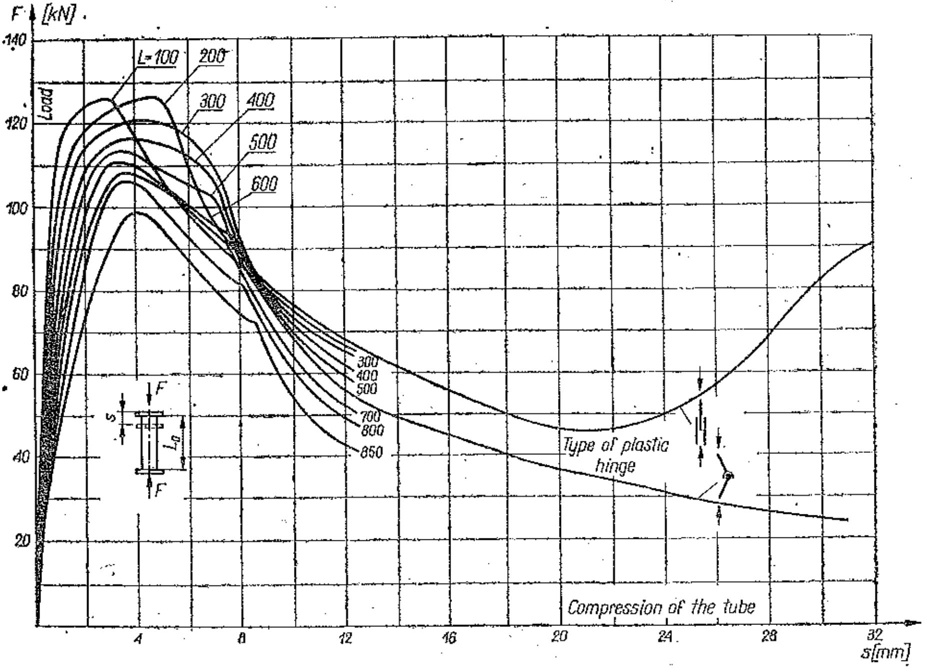

FIG. 7. Effect of tube length on the hinge characteristics.

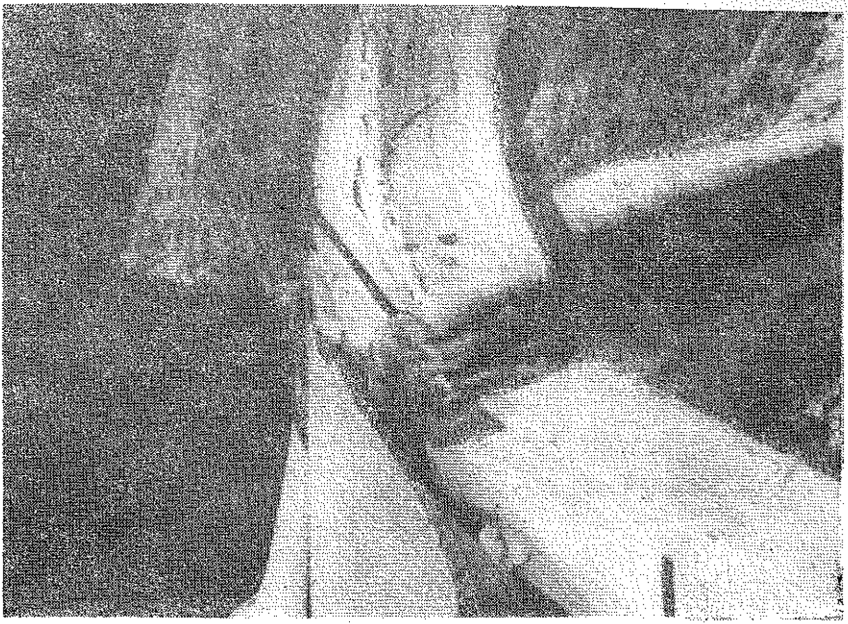

FIG. 8. Folding type hinge formed on an experimental bus having been crashed.

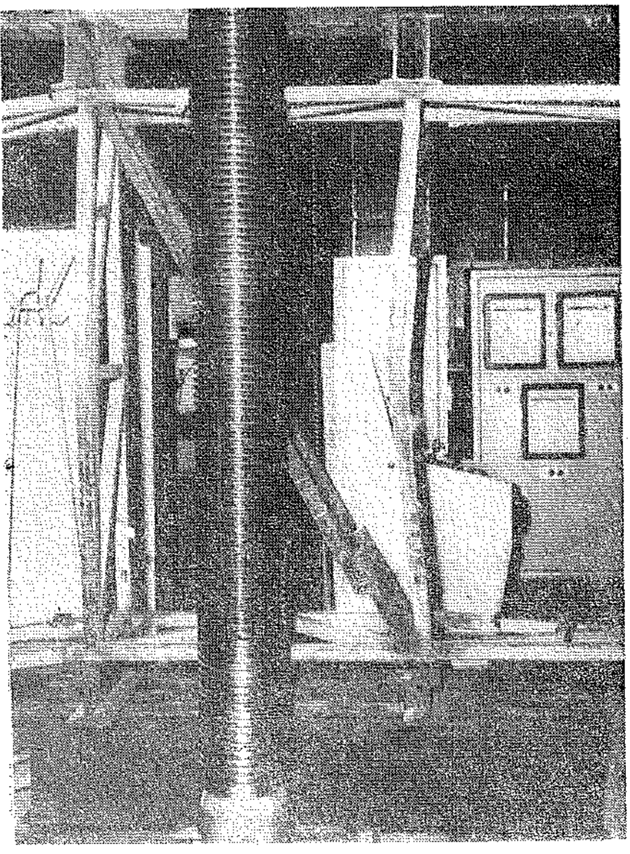

FIG. 9. Plastic hinge formed on a real bus underframe structure.

The force $w(s)$ is called the energy density function. The average energy density $\bar{w}$ is defined by

$$\bar{w} = \frac{1}{s} \int_0^s w(s)\, ds, \tag{2.1}$$

while the total energy absorbed by deforming the structure through the distance $S_{\max}$ is equal to

$$W_\Sigma = \int_0^{S_{\max}} w(s)\, ds. \tag{2.2}$$

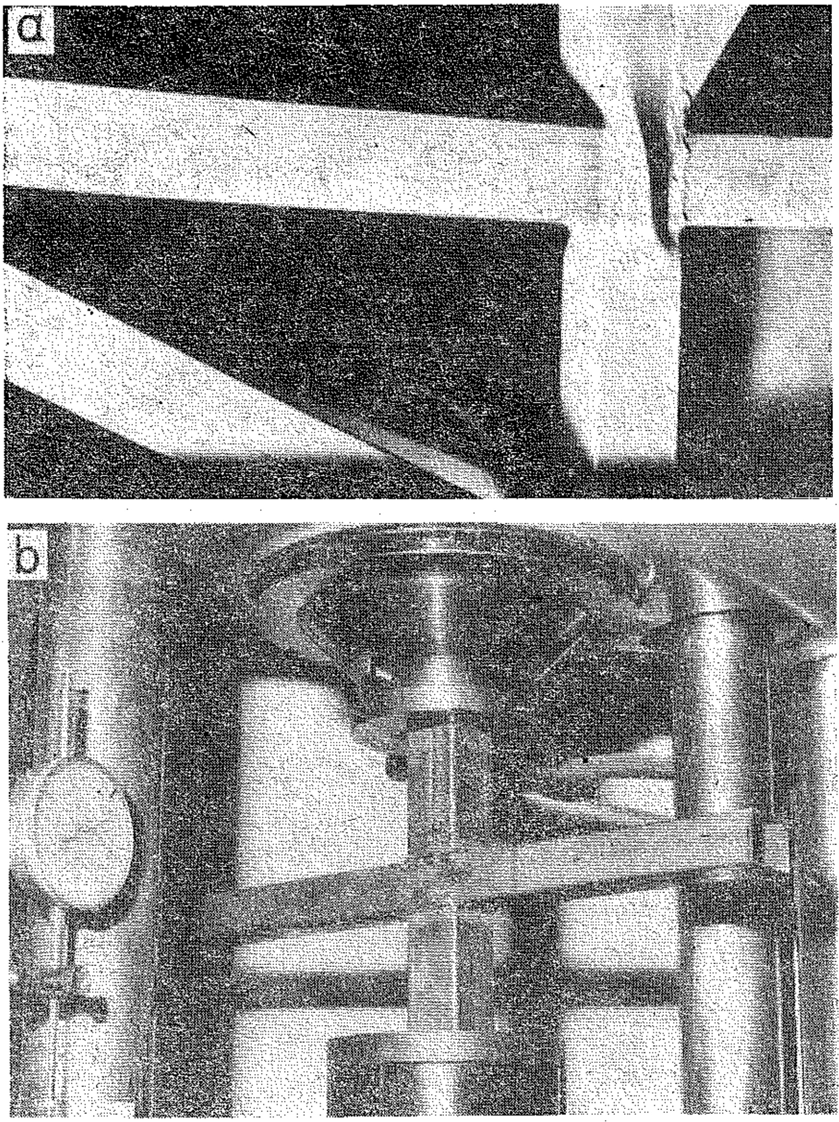

FIG. 10a, b

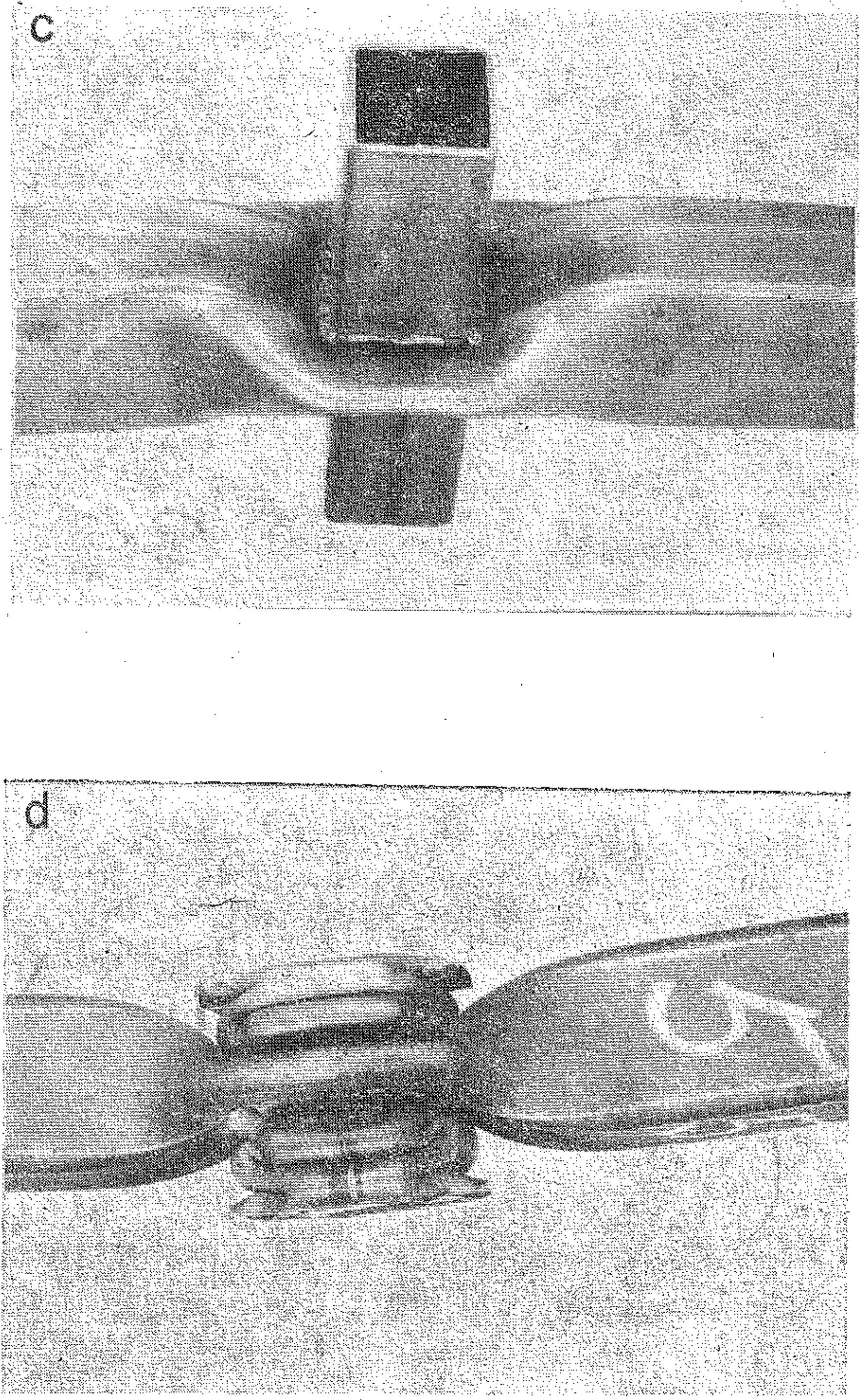

FIG. 10. Buckling of column, compressed by rails: a) real structure, b) before laboratory test c) the capability of deformation is exhausted, d) folding type hinges on the rails, combined plastic hinges.

The buckling load is influenced by several accidental effects like geometrical, manufacturing and material imperfections. Therefore, the hinge characteristics should be studied as a random process and its parameters should be described by probability distribution functions.

3. COMPRESSED PLASTIC HINGES

Two types of plastic hinges can be distinguished, depending on the length of the tube, in the case of symmetrically compressed tubes, Fig. 3. The occurrence probability of the folding-type hinge (see Fig. 1a) is shown as the function of the tube length with fixed and free ends. If the tube length is less than a critical value ($L<L_{c1}$), only the folding-type hinge is expected with a 100% probability, and if it is larger than the other critical value ($L>L_{c2}$), only the local buckling type hinge (see Fig. 1b) is observed. Between these critical lengths the first type of joint has an occurrence probability of P, while the second one $1-P$.

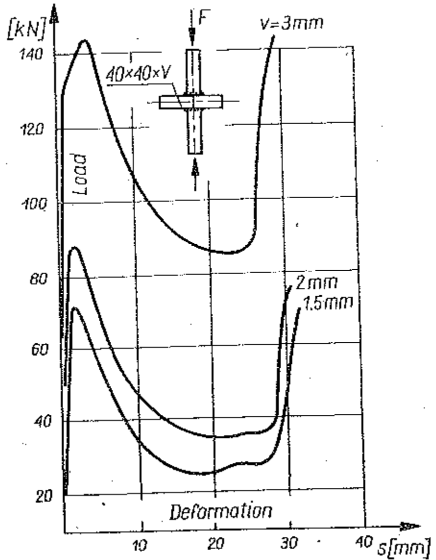

FIG. 11. Effect of wall thickness on the buckling of the column.

The folding type hinges have been discussed in a number of papers [1, 2, 3, 4]. A distinctive feature of these joints is the fact that during the loss of stability, which means the formation of more foldings following each other, the longitudinal axis of the tube does not change. A typical joint characteristics is shown in Fig. 4 for a tube with a cross-section of 40×40×2 mm and a length of 160 mm. Figure 5 gives an idea about the scatters of the test results showing the distribution function of the local maxima of the joint characteristics. The distributions were plotted on Gaussian probability paper on the basis of ten test results.

On the longer tubes the plastic hinge develops as a local plastic buckling and the longitudinal axis of the tube is broken. A typical joint characteristics can be seen in Fig. 6 for a tube with fixed ends and a cross-section of 40×40×2 mm and a length of 600 mm. For this type of hinge the shape of the joint characteristics depends strongly on the length of the tube as it is illustrated in Fig. 7. All the curves represent the average of 5 measurements. On the shorter tubes the folding type plastic hinge was observed and the tube length did not affect the value of the initiation load and generally the load parameters. The joint characteristics of the local buckling type shows some interesting features when the tube length is increased: 1) the initial load decreases; 2) the stiffness of the initial, elastic part of the joint characteristics decreases and differs more and more from the linear behaviour; 3) the development of the plastic hinge requires smaller load while the length of the local buckling wave remains the same; 4) the energy absorbing capacity decreases. Figure 8 shows the plastic hinge on the rails under the side window of an experimental bus which was impacted against a concrete obstacle, and Fig. 9 shows the front part of the underframe structure of an experimental bus on which a plastic hinge was formed during the simulation of the head-on impact.

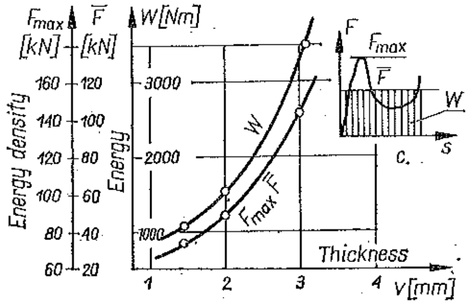

FIG. 12. Parameters of joint characteristic, as a function of wall-thickness.

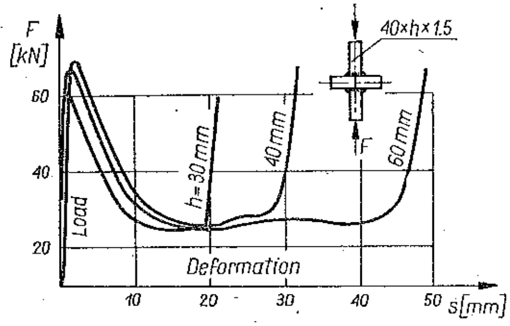

FIG. 13. Effect of tube-width on the buckling of the column.

The plastic hinge according to Fig. 1c can be found very often on pillars and columns compressed by rails from both sides. Figure 10 shows three stages or a test in which the above mentioned hinge was produced. Figure 11 presents the effect of the wall-thickness on the hinge characteristics at this type of plastic hinge for tubes with a cross-section of 40×40 mm It can be seen that the "working range" of the hinge practically does not change (about 30 mm) but the initiation load and the absorbed energy increases progressively (See Fig. 12). Figure 13 shows the effect of the width of the column h: the initiation load and the energy density does not change with an increase of the dimension h, but the working range and consequently, the absorbed energy increases.

4. COMPRESSED AND BENT PLASTIC HINGES

The plastic hinge illustrated in Fig. 1f has some analogy to the hinge shown in Fig. 1b. One essential difference has to be pointed out: the hinge of Fig. 1b is formed by pure compression, some additional bending moment appears only after hinge has been developed. The plastic hinge of Fig. 1f is created by mixed compression and bending. This type is one of the most frequently observed plastic hinges on damaged bus structures. Figure 14 shows the underframe structure of a city bus

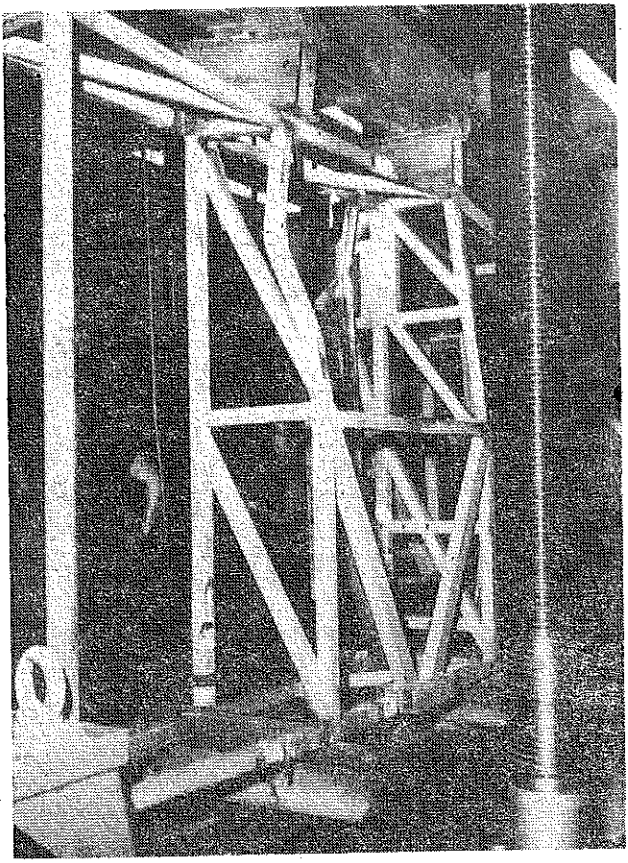

FIG. 14. Plastic hinge formed on real bus underframe structure.

which was subjected to a head-impact force. The plastic hinges were formed on the inclined rails of the structure. The shape of hinge characteristics of this type of plastic hinges is very similar to that of the pure compression type (see Fig. 1b), only the force level depends on the ratio of the compression and bending moment. A series of tests was made on tube specimens of 40×40×2 mm and fixed ends

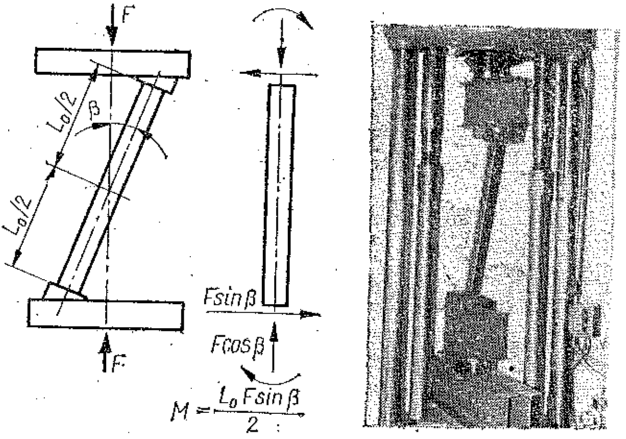

FIG. 15. Compressed and bent tube (laboratory test).

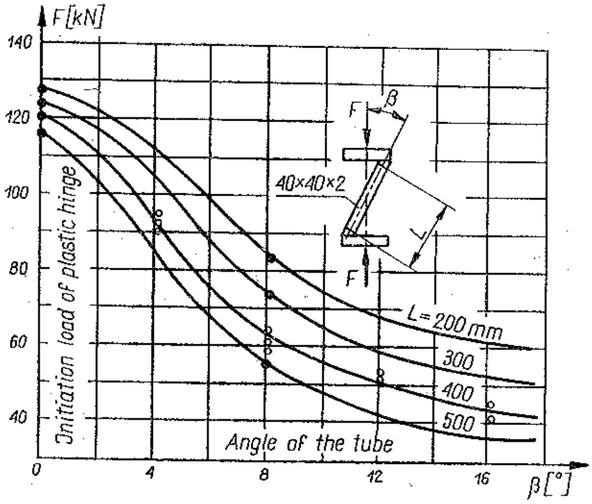

FIG. 16. The effect of additional bending moment on the initial load of plastic hinges.

to examine this problem. Figure 15 shows the specimens. The initial bending moment was increased by increasing the length of the tube (L) as well as its angle (β). As an example Fig. 16 shows the decreasing of the initial load of the plastic hinge in the function of the bending moment, which is expressed by the parameters β and L.

5. BENT PLASTIC HINGES

This type of plastic hinge (see Fig. 1d) has already been discussed by several authors [5, 6]. Figure 17 shows some of our earlier tests with tubes of 40×40××1,5 mm, while the typical hinge characteristics can be seen in Fig. 18. One type of specimen was a tube simply connected and welded to another perpendicular tube,

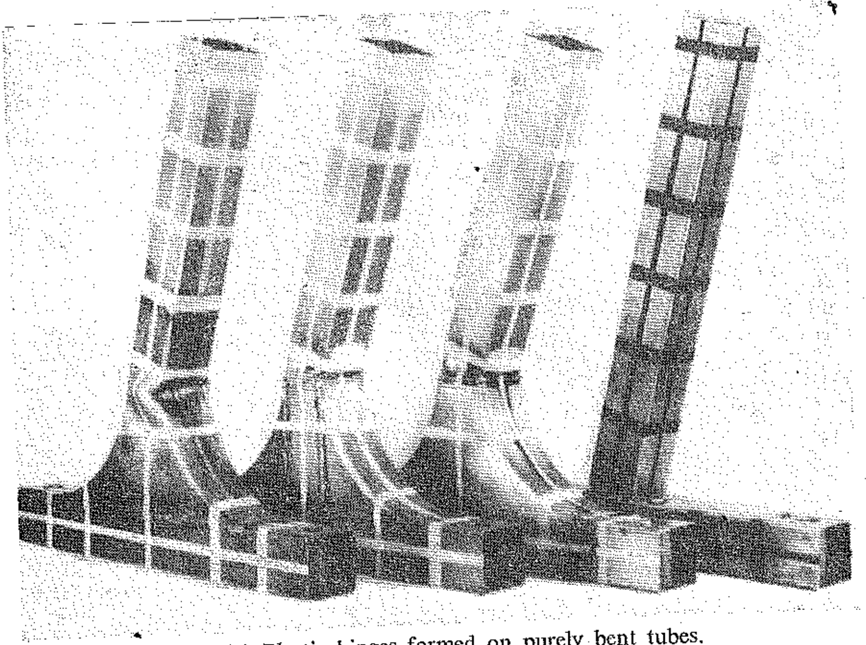

FIG. 17. Plastic hinges formed on purely bent tubes.

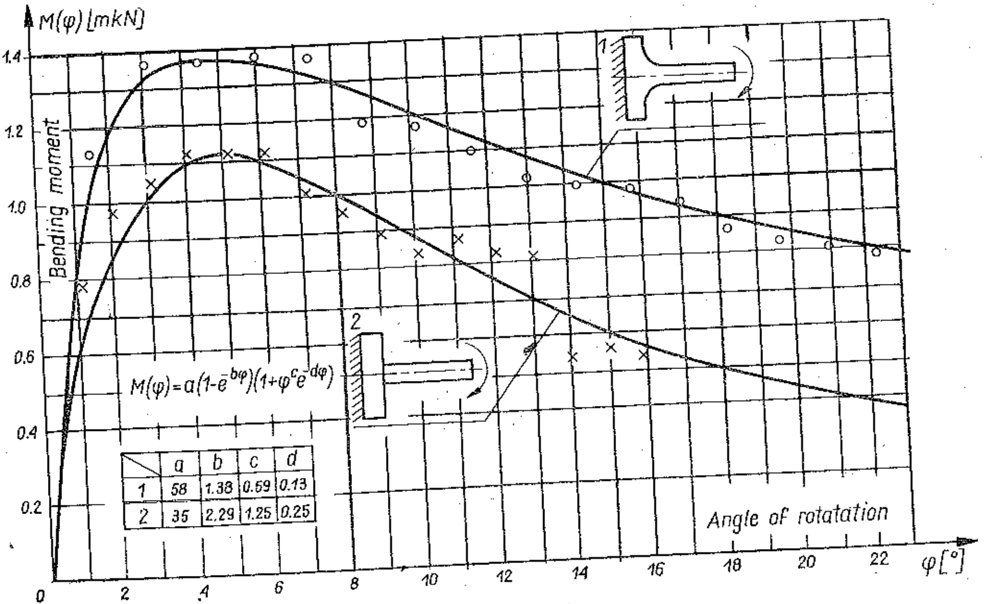

FIG. 18. Joint characteristics of purely bent hinges.

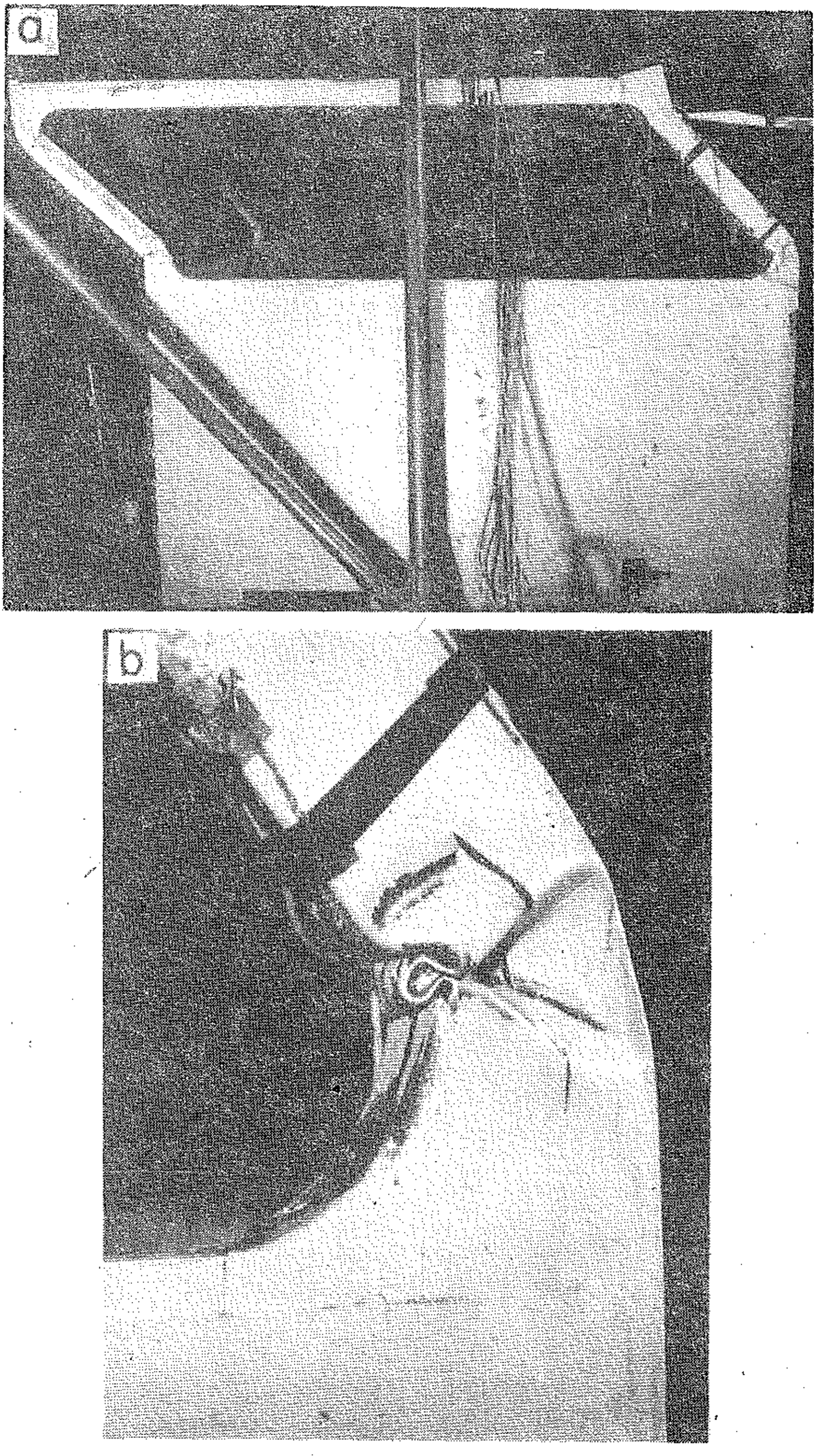

FIG. 19. Bent-type plastic joint, formed on full scale structures: a) general view, b) the plastic hinge.

and the other one had a rounded part at the connection. This type of hinge characteristics is rather similar to the ones previously discussed (for example see Fig. 7). This contributes significantly to the strength of the bus superstructure. The collapse and energy absorption of window pillars in buses subjected to roll-over is due to this type of plastic hinges. One example is shown in Fig. 19.

6. COMBINED PLASTIC HINGES

Figure 1e shows schematically a combined plastic hinge: one bent and one compressed plastic hinge connected in series. The formation of such a kind of hinge was observed on the front rail of a bus driver compartment (under the windscreen

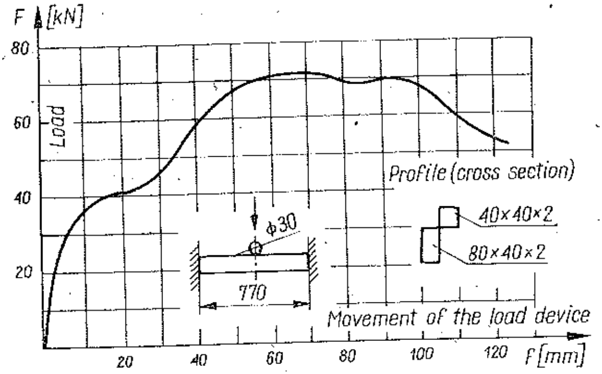

FIG. 20. Joint characteristic of combined plastic hinges.

Table 1.

Type of plastic joint			Length of tube [mm]	Remarks	Considered max. deformation s_M [mm]
Number	Figure number	Description			
1	1/a	Centrally compressed tube with folding type plastic joint	160	Free end of tube	115(*)
2			100	Fixed end of tube	50(*)
3	1/c		200	Fixed end of tube	125(*)
4	1/c	Pillars compressed by rails	width of tube 40		32(*)
5			width of tube 60		48(*)
6	1/b	Centrally compressed tube with local buckling type plastic joint	600	Fixed end of tube	300
7			850		
8	1/d	Beended tube (window column) with local plastic joint		rounded end of tube	(23°)
9				without rounded end	

(*) In this case $S_M = S_{max}$

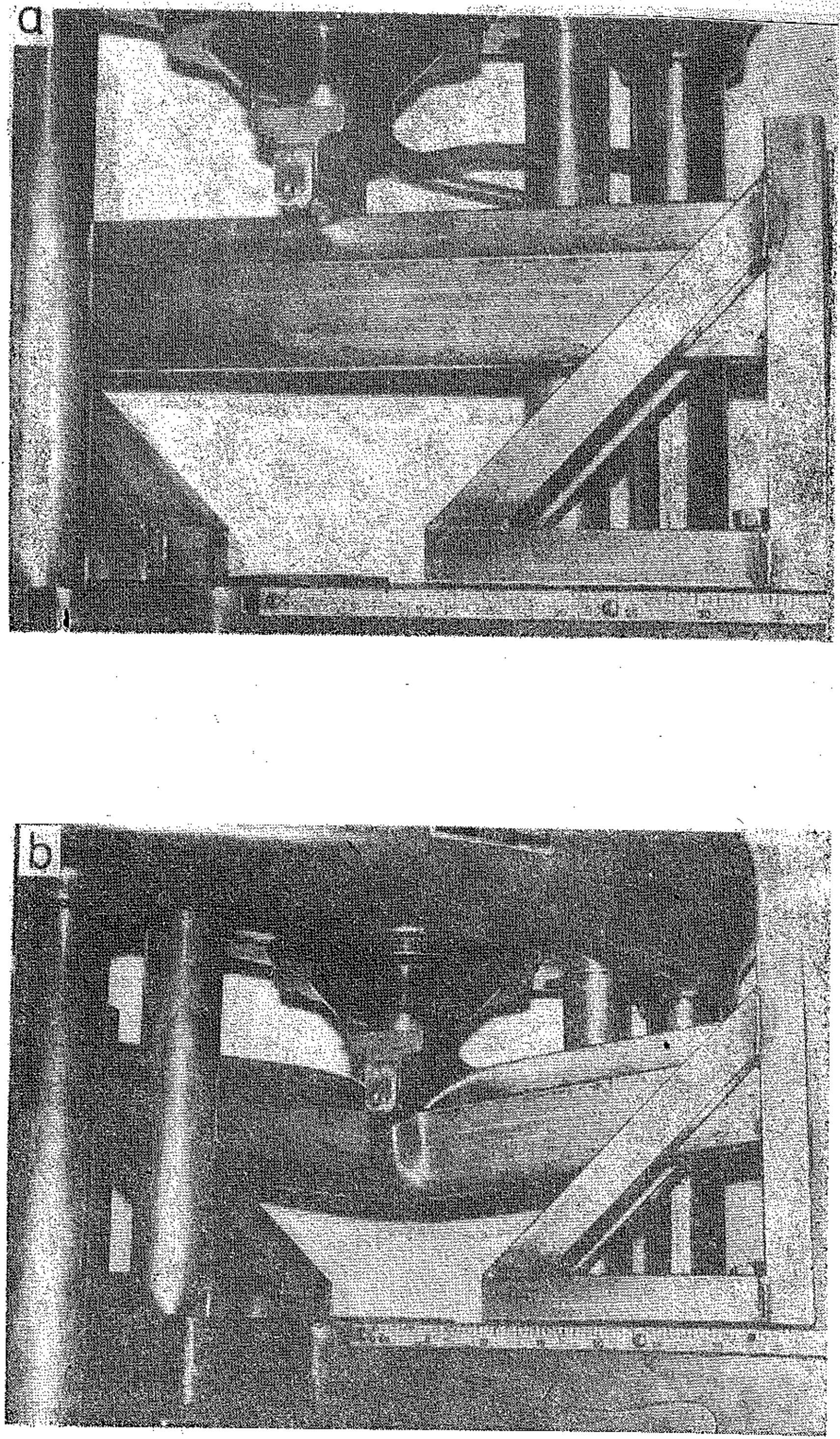

FIG. 21. Combined, connected in series plastic hinge: a) early stage of the test, b) both plastic hinges are already formed.

Table 2.

Number according to Table 1	Relative deformation parameters			Absolute parameters			Relative force parameters		Energy parameters			
	$\frac{S_1}{S_M}$	$\frac{S_0}{S_M}$	$\frac{S_{II}}{S_M}$	F_0 kN (M_0 mkN)	$\bar{F}$ kN ($\bar{M}_0$ mkN)	F_a kN (M_a mkN)	$\frac{\bar{F}}{F_0}$	$\frac{F_a}{F_0}$	W_Σ mN	W_I mN	W_{II} mN	$\frac{W_I+W_{II}}{W_\Sigma}$
1	0.01	0.02	0.02	155	65	46	0.42	0.3	7450	60	400	0.06
2	0.02	0.06	0.07	125	74	63	0.59	0.50	3690	55	308	0.10
3	0.01	0.04	0.05	125	70	55	0.56	0.44	8700	84	492	0.07
4	0.02	0.05	0.10	70	35	27	0.5	0.38	1120	125		0.11
5	0.01	0.06	0.08	67	33	25	0.5	0.37	1570	165		0.10
6	0.06	0.11	0.27	111	53	25	0.48	0.22	1600	110	535	0.40
7	0.10	0.13	0.28	98	44	10	0.45	0.11	1340	166	482	0.48
8	0.08	0.22	0.35	(1.38)	(1,07)	(0,58)	0.77	0.42	430	160		0.37
9	0.10	0.22	0.30	(1.12)	(0,75)	(0.35)	0.67	0.31	265	100		0.38

which was made of two rectangular thin-walled tubes. The hinge characteristics is shown in Fig. 20. The development process of this hinge can be seen in Fig. 21. Probably the hinge characteristics of the combined hinge may be derived from that of the elementary hinges, but surely not through a linear superposition. Although a lot of combined hinges can be immagined and a number of hinge characteristics realizations exists, all of these show the same general regularities.

7. COMPARISON OF SEVERAL TYPES OF HINGES

On the basis of our test results discussed before the main parameters of several types of plastic hinges can be compared.

For describing hinge characteristics, it is convenient to introduce the exponential-type function. The appropriate equations in various publications are different from each other, depending on the type of plastic hinge and on the assumptions and approximations used by the authors. The following four-parametric empirical equation seems to describe adequately the hinge behaviour:

$$w(s)=w_a(1-e^{-bs})(1+s^c e^{-ds}), \tag{7.1}$$

where w_a is the horizontal asymptote of the hinge characteristics and b, c, d are constants. This equation involves as a special case the formula used by TIDBURY [7] if $c=0$ and $s>s_0$. The resulting theory is based on the assumption that the initial part of the joint characteristics is linearly elastic. Our experiments indicate that this assumption is not valid in many cases.

Using only small values of s where the effect of the asymptotic value w_a can be neglected, the unity in the bracket is negligible as compared to the product and in the same time b tends to infinity. Thus we can get the equation suggested by VOITH [6].

A comparison of several types of plastic hinges is given in Table 1. In the last column s_M denotes the tested working range of the plastic hinge and if it is equal to the possible working range, it is marked by a star.

Table 2 summarizes the compared parameters. On the basis of these the following conclusions can be drawn: 1) the purely compressed plastic hinges (order number 1-5 in Table 1) strongly differ from the bent type hinges; the initiation of the purely compressed hinges is accomplished in the first 10% of the complete working range, while this value is about 30% in the case of bent hinges; 2) the energy absorbed up to formation of the plastic hinge is below 10% of the total energy absorption in the case of purely compressed hinges and equals about 40% in the case of bent hinges; 3) the specific energy density ($\bar{F}$) and the total absorbed energy (W_Σ) are also more advantageous in the case of purely compressed hinges; 4) the relative energy density ($\bar{F}/F_0$) has a value about 0.5 with a certain scatter, only the purely bent hinges differ from that assuming the value of 0.7.

REFERENCES

1. A. WIMMER, *Einfluss der Belastungsgeschwindigkeit auf das Festigkeitsund Verformungsverhalten von Blechkonstruktionen am Beispiel von Kraftfahrzeugen*, ATZ, **10**, 281–285, 1975.
2. T. ÅKERSTRÖM and T. WIERZBICKI, *Dynamic crushing of strain rate sensitive box columns*, Proc. of 2nd Conf on Vehicle Structural Mechanics, 19–31, Southfield, 1977.
3. CS. MOLNÁR, *Plastic deformation and energy consumption at dynamic (impact) loads*, Proc. of the Conf. of PSV-s, Cranfield, UK C148/77, 145–152, 1977.
4. M. MATOLCSY and CS. MOLNÁR, *Energy conditions in frontal collisions of buses*, Proc. of Conf. on Vehicles and Sciences'75, Beograd, 113–134, 1975 [in Russian].
5. D. KECMAN, *Bending collapse of rectangular section tubes in relation on the bus roll-over problem*, Ph. D. Thesis, Cranfield Institute of Technology, School of Automotive Studies, 1979.
6. A. VOITH, *The safety of the passengers in the case of bus roll-over accidents*, Thesis of Univ. Doctor degree, AUTÓKUT, 1976 [in Hungarian].
7. G. TIDBURY, *The strength of the superstructure of buses*, Proc. of the 6th Conf. of Bus Experts, Budapest, 216–224, 1975.

STRESZCZENIE

ZACHOWANIE SIĘ PLASTYCZNYCH PRZEGUBÓW W CIENKOŚCIENNYCH KOLUMNACH

W pracy omówione są różne postacie plastycznego zmierzenia cienkościennych pryzmatycznych kolumn poddanych ściskaniu lub zginaniu ze szczególnym zastosowaniem do projektowania ram i nadwozi bezpiecznych autobusów. Dla ściskanych rur wyznaczona została doświadczalnie krytyczna długość określająca przejście z lokalnej do globalnej postaci wyboczenia. W przypadku zginania elementów zaproponowano prostą zależność empiryczną pomiędzy momentem zginającym a kątem obrotu w przegubie. Badano również zachowanie złączy poddanych jednoczesnemu ściskaniu i zginaniu. Uwzględniono również efekt imperfekcji poprzez opis charakterystyki przegubu za pomocą losowej funkcji dystrybucji.

Резюме

ПОВЕДЕНИЕ ПЛАСТИЧЕСКИХ ШАРНИРОВ В ТОНКОСТЕННЫХ КОЛОННАХ

В работе обсуждены разные виды пластического сдавления тонкостенных призматических колонн, подвергнутых сжатию или изгибу, с особенным применением для проектирования рам и кузовов безопасных автобусов. Для сжимаемых труб экспериментально определена критическая длина описывающая переход из локального к глобальному виду продольного изгиба. В случае изгиба элементов предложена простая эмпирическая зависимость между изгибающим моментом и углом вращения в шарнире. Исследовано тоже поведение соединений подвергнутых одновременному сжатию и изгибу. Учтен тоже эффект имперфекции путем описания характеристики шарнира при помощи случайной функции дистрибуции.

RESEARCH INST. OF AUTOMOBILE INDUSTRY, AUTÓKUT
BUDAPEST, HUNGARY

Received February 15, 1980.