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Tests and test methods of bus crashworthiness considering specially the roll-over safety, the plastic hinges and zones of bus frameworks

Ph.D Thesis Summary

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1. Research preliminaries, basic definitions

Plastic deformation feature of ductile metals are is used by traditional hot and cold forming technologies (e.g. blacksmithing, rolling, die forming,…) for centuries. Plasticity, with other word: ductility means the feature of materials that they are able to change their forms, geometries by effect of mechanical loading without fracture and crack, without crystal-structure crack and breakage of atomic bonds, keeping the material continuity.

Ductility is not absolute feature of the material. It is function of condition's characteristics as stress, temperature, plastic deformation speed.

Comparing the tensile diagrams and the ductility's features of different metals, that metal can be cold-worked well which has big elongation and contraction. Due to the loading demand that metal has an advantage whose tensile curve is flat.

Due to the theory the plastic deformation could be explained by sliding of atomic planes, by atomic dislocations. The energy required to break a single bond is far less than which required to breaking all the bonds on an entire plane of atoms at the same time. Even the force required to move a dislocation shows that plasticity is possible at much lower stresses in defected crystal than in a perfect crystal due to the real test results. This contradiction was solved with theory of dislocation developed by *Vito Voltera* in 1905 and his theory was extended to the metal cold-working by *Orován Egon (1902-1989), Polányi Mihály (1891-1976)* and *G. I. Taylor* independently in 30s of last century. [1]

Dislocations are linear defects around which some of the atoms of the crystal lattice are misaligned. Dislocations are ready to move and interact under the influence of stresses induced by external loads that leads to the characteristic malleability of metallic materials. Due to the stress individual atoms of dislocations "jumping" into vacancies, climbing occurs in single atom diameter increments, one row of atoms entirely roll over on the other row of atoms.

The vehicles, especially the utility vehicles and specially the buses and coaches are built with thin-wall rectangular metal tubes.

The metal material in a vehicle structure can be deformed reaching the yield stress due to the pressure, bending or torsion loading. Its form and geometry are significantly changing, the material is "crumpling" and so-called plastic hinge is created.

For the plastic hinge has no internationally accepted "terminus technicus" word, the most detailed description can be found at *Matolcsy*. [43] Based on his determinations, slightly changed and partly composed them, I use the next definitions in my dissertation:

a. *Elementary plastic hinge* is generated on rod-like elements (where the length of element is much bigger than the two other dimensions) due to simple loading. The load causing stability loss creates plastic deformation in relatively small section; the original cross-section is essentially deformed; the dimension of deformed plastic hinge is bigger as cross-section of rod-like element. The elementary plastic hinges can be divided and described by the direction of deformation as: linear, rotation or complex plastic hinges.

b. *Individual plastic hinge* is formed in such non-rod type elements which have no one emphasized (longitudinal) direction, this happens with metal sheets' buckling or side-crushing of rectangular tubes. Mostly one-time complex loadings arise it in these cases and cause crumpling, stability loss. The extension of individual plastic hinge is not as regular as the elementary one is.

c. *Combined plastic hinge* or *plastic zone* can be realised in special compound structures, built up from combination of metal sheets, open or closed sections of structural profiles. In this case the stability loss is caused by not only one elementary or individual plastic hinge. More than one local bucklings take place and the loss of stability is the collective result of them. The sequence of local bucklings drives to the entire collapsing of structure. The combined plastic hinge may include elementary and individual hinges too. Generally it is meaningless to talk about the length of combined plastic hinge, it has only extension.

2. Exposition of research subject

At frontal impact and roll-over accidents the metal sheets, open and closed profiles of vehicle structures are deformed, residual deformations are occurred in consequence of the above discussed plastic hinges.

In my dissertation I study and research the initiations and developments of thin-walled metal profiles' plastic hinges, energy-absorbing features, their characteristics due to different types and directions of loadings.

With experimental methods I measure and analyse the plastic hinges' characteristics at frontal impact and roll-over of buses, I research how possible to fit better and bigger energy absorbing bumper, how to calculate numerically the bus structure' absorbed energy with static tests by conservative method and how can I increase the energy absorbing capability of rectangular thin-walled metal tubes.

Subject of my dissertation, in the exact and strict sense, is to test and assay the plastic hinges of rectangular and quasi-rectangular steel tubes of bus structures.

3. Literature survey, research-place premises

The worldwide vehicle safety researches (active, passive safety) have been started only in the second half of 60s last century. First of all these researches have aimed to increase the safety of passenger cars and the goal was to reduce the (fatal) accidents numbers with developments of new safety cars. In 1966, after establishing the NHTSA (National Highway Safety Administration), was started to issue the new motor vehicle standards FMVSS in the USA.

In 1969 the so called *Experimental Safety Vehicle* (ESV) program was designated. In 1991 the ESV abbreviation was a bit changed and backronymed to *Enhanced Safety of Vehicles*. In 1971 the first ESV conference was organized on vehicle safety (active, passive and passenger safety) subject and this is the biggest two-yearly organized research forum in this field.

Hungary did not participate directly in the international automobile development co-operations, but initiating by the development demands of Ikarus 200 type bus-family and the government-backed bus-development program we have joined the leader European countries with our developments due to the field of bus manufacturing technology and passive safety (roll-over, seat and seat anchorage strength, frontal impact) researches. Hungary has become a bus-expert country in the last 40 years.

The internationally acknowledged success-story of the Hungarian Bus and Coach Expert Meeting was started in the same time, in 1971 which was (is) three-yearly organized in international level. It was the first comprehensive conference in this subject in Europe. Numerous initiations and substantive works for bus safety regulations can be related to home experts and especially to the Bus Department of AUTÓKUT which was the professional engineering centre of bus researches. (I have worked for this department too.)

Thanks for the early and continuous home passive safety researches Hungarian engineers have dealt with the requirements of crashworthiness concerning the bus structures.

First of all among the foreign researchers we have to mention the names of *Davis, Chang, Wierzbicki, Mahmood, Paluszny* due to the mathematical and theoretical shell-modelling of plastic hinges and besides them we can meet the papers of *Abramovicz, Pifko, Vignjevic* due to the questions of loading, energy absorbing of plastic hinges. [4-15]

Simultaneously significant results and papers were born at home too, dealing with vehicle structural plastic hinges. What is more we can say that the passive safety researches of buses have started here and become international. In this subject, mathematical description of the functional mechanism and characteristic approach of plastic hinges or thin-walled rectangular tubes' plastic hinges effects on bus structures connected to frontal impacts and roll-overs, we have to emphasise Hungarian researchers too, first of all referencing works of *Molnár, Matolcsy, Voith.* [32-38]

The energy absorbing capability of plastic hinges due to the static and dynamic loading is important task, which is widely used by up-today finite element techniques as LS Dyna, Pam Crash, but technical literature's background is deficient. The experimental background is also non-appropriate for such a dynamic energy absorbing task because the tests are carried out with vertical drop-masses or a bit better way with horizontal flying masses. Due to the results of flying masses tests on axial crushing of mild steel square tubes, to reach the same plastic deformations by dynamic load with 6-10 m/s impact speed as it can be reached by static load, it needs 10-30 % more energy. (See *Kim* and et. [25])

The bus frontal impacts and roll-overs were outstanding subjects in International Bus and Coach Meetings and the most reputable foreign researchers *Kecman, Wierzbicki, Tidbury, Aparació, Sadeghi* have appeared with their papers here. [16-20]

The plastic hinges' behaviours in combined structures according to automobiles can be studied in *Hollowell, Prasad, Zeidler* works. [21-24]

Hungary has started among the firsts with the questions of bus crashworthiness and we have carried out numerous tests in this field. (The bumper and roll-over tests have directly served the better cognition of plastic hinges' behaviours.) The outstanding home representatives of bus safety are *Matolcsy, Molnár Cs., Voith, Pintér, Batiz, Véssey* who, many times before the foreign researches, have enriched and helped the creation of new bus regulations with numerous new ideas and results. [28-31] [38-50]

Many ideas and conceptions were born for the requirements of bus roll-over safety and the common principle and basic of the simplified test methods have driven the control to the sequence of plastic hinges. Common feature is to display the plastic hinges' characteristics in mathematical forms and built them to the computer models. [13] [19] [42]

Validation of these simulation models can be only done with experimental measuring of adequate and acceptable numbers of plastic hinges.

Simple and effective solution for increasing absorbed energy of plastic hinges is to enlarge the thickness of given outer dimensional profile. It can be done in the design process or if the profile parameters are fixed the inner space of section can be filled with light, hardly compressible material.

In the literatures there are *Santosa* [26-27] papers, who has filled steel tubes with aluminium foam and the 0,55 kg/dm3 density foam has doubled the absorbed energy at bending tests.

4. Main objectives, test methods

4.1 Description of the task, significance and actuality

In this paper my researches aim to improve the adaptability of bus frame elements, structures, to increase the energy-absorbing capability of plastic hinges

- in case of bus frontal impact by axial loads and
- in case of roll-over of bus by basically bending loads.

The aimed tasks, the tests of plastic hinges, were carried out partly on simple frame elements, partly on frame-structure's units or on complete buses. (Measuring accuracy of plastic hinges can be increased with measuring more coherent and together-working plastic hinges at the same time, e.g. a given cross-segment bending test and controlling the interaction of plastic hinges too.)

Significant parts of the researches were:

- working out special procedures for increasing energy absorbing capabilities of plastic hinges of structural units due to the axial and bending loads,
- controlling, testing and comparing of prescribed and applied test methods of bus roll-over safety, critical analyses and determination of measuring accuracies of them,
- developing a new test method for bus superstructure roll-over strength.

My experiments, due to the numbers of plastic hinges, were carried out in three complexity levels:

- with single thin-walled rectangular steel tube's test of elementary plastic hinges, measuring the plastic hinge' characteristic one by one,
- with more (typically 8-32 pieces) simple and multiple plastic hinges and zones of bus frame cross-segments, and
- with tests of (typically 24-100 pieces) plastic hinges and zones on complete bus frameworks.

The primary program was to ascertain the working mechanism of plastic hinges and modification possibilities of their characteristics. The significance of this can be practiced in the field of bus crashworthiness. The realisation of better connected bumpers, the development of roll-over safety test methods and the structural developments for improved roll-over safety give the actual real possibilities.

4.2 Test methods, applied procedures

The used test methods were the laboratory basic methods of experimental mechanics: static compression and bending tests, dynamic pendulum and frontal impact tests and different (static, dynamic) types of roll-over tests on complete buses and bus structural components.

The laboratory measurements have happened with analogue (acceleration, load, displacement, strain) transducers, using analogue and digital amplifiers and data-recordings were done with analogue cassette tape recorders and digital computers.

5. New scientific results (Theses)

5.1

I have proved with impact and compression tests that better, more adaptable bumper, energy absorbing elements can be made with larger energy-absorption capability from pre-compressed thin-walled rectangular steel profiles than from normal ones and I have developed a production procedure for manufacturing them.. [S1-S7]

I have examined thin-walled rectangular and quasi-rectangular steel profiles (side ratio: a/b≤ 2, thickness: t ≤ 2 mm) formatting plastic hinges with large deformations due to the static axial loads. I have assumed that the peak load of first plastic hinge is more than 50% higher than the peak loads of next (second, third, fourth,…) successive plastic hinges. Applying this feature I have verified that pre-compressed steel profiles are able to absorb 30% more energy than the normal profiles compressing them over the first plastic hinge's peak till the level of second plastic hinge's peak due to pre-determined stability loss load. I have worked out a procedure for manufacturing of energy absorbing elements: pre-compressing the closed hollow-sectioned profiles, which length is less than the buckling-limit, by cold forming, and creating only one round-type buckling till the load falls off under the level of 2^{nd} plastic hinge's peak load. From my axial load-type tests has come out that small dimensional-deviation ($3\text{-}5^{o}$ parallel difference of the end sides at a 220 mm long profile) have influenced the plastic deformation process. If the first plastic hinge starts to form properly then the second and the following plastic hinges are formed regularly too. If the first plastic hinge starts to form with one-side crumpling in that case the multiple plastic hinges formation does not occur, the plastic deformation will be ended with lateral buckling. I have assumed that the pre-compressed profiles possessing first plastic hinges, comparing with the normal ones, have not only better fitting-characteristics by energy absorbing viewpoint but their deformation abilities by further plastic deformation process are also better concerning the load-direction and sensitivity.

5.2

Experimental tests have demonstrated that energy absorbing capabilities of extended metal structures with individual supports can not be accurately assumed. [S8-S11]

Plastic deformation processes of extended, rigidly supported (2,5 m wide, 2-3 m height, 1-1,5 m long) metal rectangular profiles-tubes-sheets structures built up from thin-walled rectangular steel profiles (side ratio: a/b≤ 2, thickness: t ≤ 3 mm) and metal sheets (thickness: 1≤ t ≤ 5 mm) were studied by pendulum tests (3500 kg mass, 3,5 m pendulum length) and by static tests. Attributes of these structures' plastic deformation processes are arising of 8-32 plastic hinges and zones during loadings. Comparing the results and procedures of pendulum and static tests I have assumed:

a. places, types and generation of the forming plastic hinges are the same at the two-type tests;
b. the portion of the initial pendulum energy causing elastic and plastic deformation in the tested structure can not exactly be calculated on the contrary of static tests; I have pointed out that the pendulum itself does not absorb calculable energy during the impact test therefore significant part of the energy of pendulum mass slips out through the individual supports from the measuring system due to undefined-open system.

It comes out from the results that the pendulum test is not applicable for accurate tests of individual, extended, different-type and partly diversely supported structures, only for comprehensive tests. Pendulum test is not applicable for measuring of energy absorbing capability of extended (bus) structures built up from metal rectangular profiles and sheets.

5.3

I have certified that conservative estimation and calculation can be done with static bending tests of extended bus frame segments for entire bus roll-over strength. [S12-S14]

Plastic deformation process and plastic hinges energy absorbing capability were examined by roll-over tests of large (8-12 m long, 2-2,5 m wide, 2-3 m height) bus structures, where the number of plastic hinges are large numbers typically between 24-100. The complex structure was divided to smaller (1-2,5 m long bus cross-segments) and these frame-segments were tested by pendulum and laboratory bending test too. In comparison of these three-type results I have clarified and assessed that the laboratory bending test of cross-segments can be used not only for correctly substituting of defective pendulum tests but it is suitable substitutive and conservative method of dynamic roll-over tests. Plastic formatting procedure and the plastic hinges succession at laboratory bending test are the same as they happen at the dynamic roll-over test. I have proved, ensuring the same energy absorbing due to the (bus) structure mass and CG position, the plastic hinges deformation extensions at static test are higher than dynamic roll-over test. From the measurements could be proved the substantial influence of manufacturing technology on measured values too.

5.4

I have worked out a new computer iteration method bus roll-over strength calculation based on the static laboratory bending of bus frame segments. [S15-S20]

Numerous elementary rotational and combined plastic hinges are formatting at roll-over of large-scaled complex structures (e.g. buses). I have revealed that divided the complex bus structure into more (typically 4-8) pieces cross-segments, some of them are doubled for easier loading, a conservative estimation can be calculated for the value of roll-over strength by laboratory bending tests. The load shall be realised by rigid plate on the roof edge of cross-segment in the same angle as the impact force arises at real roll-over test. The plastic deformation process is repeatable and it can be handled and followed easily measuring the energy absorbing characteristics of plastic hinges of given cross-segment.

I have worked out a calculation method for the complete (bus) structure deformation process using the static laboratory bending test results of individual cross-segments. The non-linear deformation characteristics of laboratory bending tests were built into a computer iteration process. It is based on real roll-over test conditions of absorbed energy and roof edge displacement. The iteration ensures the remaining of roof edge points in one line which is basic feature of roll-over test, and it contains the plastic hinges positions of side columns and the continuous control of the deformation-energy absorption as initial conditions of the calculation procedure. This way the final result on the complex structure approaches the required value of roll-over safety in conservative mode. It gives larger deformation of the side columns as it occur at the real roll-over test.

5.5

My experiments have certified the steel rectangular tubes energy absorbing capabilities can be improved with filling up with artificial resin after manufacturing of structure without any metal-structural changing. [S21-S24]

I have examined thin-walled rectangular and quasi-rectangular steel profiles (side ratio: a/b≤ 2, thickness: t ≤ 2 mm) formatting plastic hinges with large plastic deformations, rotational hinges due to the static bending loads. I have assumed that the energy absorbing capability of plastic hinges significantly, by more than 30%, can be increased and simultaneously the peak loads can be increased with 20% in the case of filling up with two-component resin. The filling in of 0,8 kg/dm^3 density, non-corrosive artificial resin into the rectangular profiles of bus side columns can be done later for increasing the roll-over strength of ready-state bus too.

6. Practical utilization of results

- I have proved with laboratory impact test that bus bumpers can be designed and manufactured with more than 30% higher energy absorbing capability, using the same free mass and structural space, from pre-compressed rectangular profiles as the current bumpers which consist of normal factory-made rectangular tubes. The experimental version of the suggested interchangeable bumper from pre-compressed profiles was made but factory application has not happened;

- the objected, disapproved pendulum test method was deleted from the approved test versions on roll-over test methods of modified ECE R66.01;

- nowadays the so-called AUTÓKUT method - based on static tests of cross-segments and computer iteration calculation - or basically similar procedures are widely used for verifying the roll-over strength of buses;

- practical applications of artificial resin filling up of bus side columns and increasing the roll-over strength have happened to Csepel Lyra and E98 type buses of Ikarus Special Coach Factory; more than 40 buses fillings have happened successfully;

- results of axial and bending loading of metal thin-walled rectangular profiles can be used for the computer estimations of loading of bus frame elements and for validations of FEM procedures of bus frames due to roll-over tests or bending loads.

Own scientific publications connected to the Thesis points

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[S3] *Vincze-Pap S.*: Autóbuszok méretezése frontális ütközésre, Anyagvizsgálók Lapja, 2003/4 szám 129-133. oldal
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