# SYNTHESIS REPORT

CONTRACT No : BREU-CT90-0362(SMA)

PROJECT No : BE-3385-89

TITLE : **TRAINCOL**

**Advanced Design of Crash Fail-Safe Train Structures Under Service and Impact Conditions**

**PROJECT COORDINATOR :** Loureiro, Rui L.

PARTNERS : SOREFAME, Portugal
GEC ALSTHOM, France
CAF, Spain
1ST, Portugal
CP, Portugal
CIC, UK
UVHC, France

**REFERENCE PERIOD FROM** 91/03/01 to 95/02/28 **REPORT No** TRAINCOL/SY

STARTING **DATE :**1991, March, 1st **DURATION :**48 months

PROJECT FUNDED BY THE EUROPEAN COMMUNITY UNDER THE BRITE/EURAM PROGRAMME

DATE: May, 1995

**SYNTHESIS REPORT**

# ADVANCED DESIGN OF CRASH FAIL-SAFE TRAIN STRUCTURES UNDER SERVICE AND IMPACT CONDITIONS

Manuel S. Pereira* and Rui Loureiro**

*Instituto Superior Técnico, Av Rovisco Pais, 10%, Lisboa CODEX, PORTUGAL
* *SOREFAME, Apartado 5, Venda Nova, Amadora, PORTUGAL

## ABSTRACT

This report describes the results of a research effort for the development and testing a new and advanced design methodology for crash fail-safe train structures under service and impact conditions.

The collision energy in a train crash is generally very large and causes not only high property damage, but also a large percentage of the injuries and fatalities associated with railroads. Though substantial efforts for improvements of active safety systems have been developed on railways in order to decrease the probability of accidents, train collisions still occur.

Project TRAINCOL focus on train collision phenomena with the aim to contribute in a decisive manner for:

- A better understanding of the crash phenomena as applied to trains, using experimental reduced scale and real size tests.
- An effective use of advanced methods of structural and dynamic analysis of train crash and impact situations.
- Development and application of modem design methodologies of train cars, including design sensitivity and optimization techniques to improve existing structures or developing new ones.
- Improvement of cost effectiveness of the design stages with a decrease of design and development cycles.
- Design and production of lightweight and anti-crash fail-safe train structures using the stiffness, collapse and energy absorption characteristics data base of structural members.
- The proposition of more advanced regulations regarding safety and integrity of railway equipment, including passenger injury assessment.

The proposed design methodology comprises different computer aided tools of increasing complexity and accuracy which can be used with greater advantage and efficiency in the different design stages of railway stock. Injury assessment capabilities have also been incorporated in order to assess the occupant/rail way vehicle injury parameters in terms of the standard injury criteria.

Formulations for the sensitivity anal ysis and optimization of 1D and 2D mechanical systems and structural systems have also been developed allowing for the design of optimum characteristics of the different energy absorption devices and anti -climbing systems.

In general, the crashworthiness design methods and associated static and dynamic software tools, which have been developed and brought together in this project, require information to be obtained from numerical or experimental crush tests of specific structural components, sub-assemblies and critical energy absorption devices normally located in the car extremities. This hybrid feature lends to the present design process various efficiency gains as a result of a better understanding of the crash and different collapse mechanisms and ease of use. Parts, components, sub-assemblies and complete vehicles have been manufactured and tested under static and dynamic conditions in order to validate new software tools and new railcar designs.

Essentially the present project has a threefold technical approach system consisting of the following:

i) Development and upgrading the experimental knowledge of train crash behavior covering static crush tests of structural sub-assemblies, components and joints and dynamic crash tests of real size and reduced scale models.

ii) Development of an appropriate set of design tools to provide a consistent iterative design methodology with increasing levels of accuracy and sophistication including modern structural optimization tools and modern methods of injury assessment.

iii) Application of different design tools in a design effort to develop and explore new railcar structural designs with the inclusion of crashworthiness requirements in the concept and early design stages.

The proposed project methodology is illustrated schematically in figure 1,

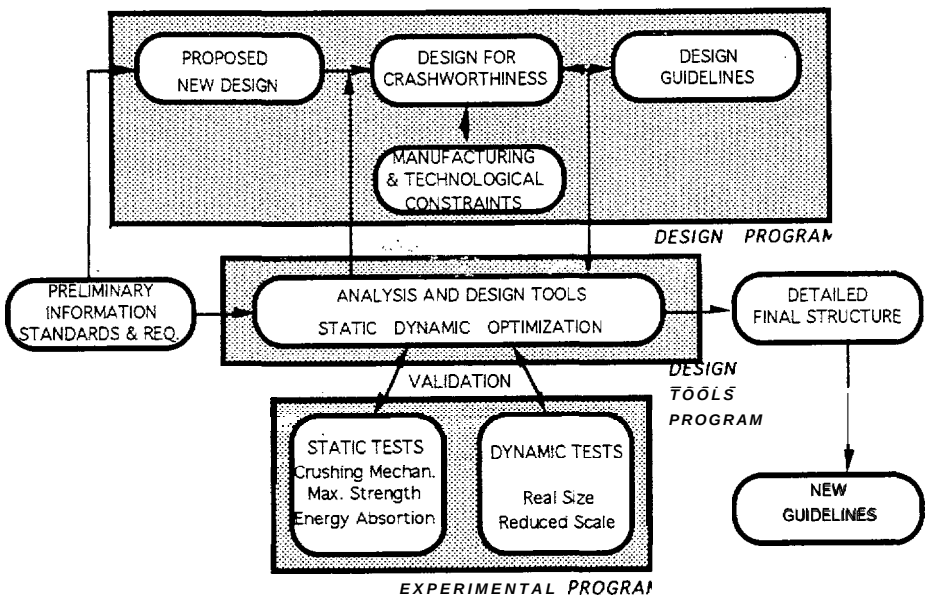


**Figure 1.** Project TRAINCOL technical approach

The underlined design methodology comprising different computer aided tools of increasing accuracy and complexity required a strong interaction between the three major programs throughout the project. These programs are now briefly outlined.

- EXPERIMENTAL PROGRAM

Parts, components, subassemblies and car extremities have been manufactured by the industrial partners and have been tested in their sites or in the installations of the French and Portuguese railway operators, SNCF and CP, using different types of testing and measurement equipment.

- MODELING AND DEVELOPMENT OF DESIGN TOOLS

Software tools have been developed with increasing level of detail, representing an effort in modem and advanced formulations in the areas of dynamic. analysis of mechanical systems as applied to impact problems including a substantial effort in structural optimization as applied to rail car structures.

- DESIGN OF NEW RAILCAR FAIL-SAFE TRAIN STRUCTURES

The industrial partners of the consortium were committed to use their design experience to develop new railcar structures to meet higher standards of safety regarding crashworthiness and service conditions. For this purpose the project itself ensures a close link between industries and research institutions which allow for an efficient integration of modem analysis and design tools in the design process. Software tools have been tested in the university environment and have been made available to the industrial design engineers and used within the consortium industries environment.

## 2. ACCIDENT DATA REVIEW. PRESENT CRASHWORTHINESS REGULATIONS

Within Europe, the requirements to ensure the structural integrity of coach bodies comes mainly from the International Union of Railways (UIC) and the affiliated European Railway Research Institute (ERRI).

For main line coaches, the UIC 566 standard specifies vertical loads as well as a number of longitudinal load cases which are intended to represent service loads and the effect of minor collisions. The main longitudinal compression static load of 2000 kN is applied on the buffers or automatic couplers. A diagonal compression load of 500 kN applied on two diagonally opposite buffers is specified and, also, compression loads of 300 kN and 400 kN are imposed to be applied on three different levels of collision and corner posts.

A study performed by the Organization of Research and Experiments (ORE ) in 1991 have established some recommendations for the conception of front cabin structures, regarding the dynamic impact behavior.

In order to mitigate the effects of collision of train rakes, general and specific requirements for structural collapse have been more recently put forward by British Rail. The proposed general guidelines specify that each vehicle end wall shall be connected to the rest of the body in such a way that the energy produced by a collision is absorbed first by deformation of the end wall section before other parts of the body are deformed. Also the vehicle shall collapse without promoting overriding and shall occur in areas not likely to be used by passengers and crew. Requirements concerning levels of energy absorption, collision compression loads and constraints on collapse distances are also clearly specified .

A review of train accident data, based on accidents reported in the literature and on the experience of train operators in France, Spain and Portugal was earned out. 52 accidents involving rail vehicles were reported, characterized and investigated. This information was necessary in order to set the starting point for the project in so far as there was a need to characterize the most typical accidents on the basis of establishing their conditions and their consequences.

A rapid analysis of the collected data shows that three major type of accidents are possible

1) Railway vehicles colliding with one another (accounting for 2/3 of the accidents);
2) Railway vehicles colliding with road vehicles;
3) Projectiles striking railway vehicles.

The general principle for end-to-end collisions with rail vehicles is that the energy for specific accidents should be absorbed by progressive and controlled deformation of the bodywork. Only end-to-end collisions will be considered because these are the ones contributing with a greater proportion of injuries.

In the proposed approach, at the onset of collision, the resulting impact forces most often act at the coupling/buffer assembly. This system absorbs a proportion of the energy up to limit of its travel and its maximum strength, after which it should collapse, allowing the ends of the vehicle structures to come into contact. This should initially involve anti-override systems so as to keep the vehicles vertically in line throughout any further deformation.

Another important classification of collisions, as suggested by ORE is presented according to energy involved ranging from .25 MJ up to 15 MJ for impacting speeds from 10 km/h up to more than 50 km/h, corresponding to simple shunting collisions and collisions at maximum speed, respectively. The vehicle structure will be designed so as to absorb the energy of an impact following the energy characteristics defined in the form of a force-displacement curve as it is schematically indicated in figure 2.

A survey of design conditions for crashworthiness of trains indicate that each country has a different structural specification, although they do observe the principles laid down by UIC in its different leaflets. Overriding is a major cause of serious injuries and fatalities. Little is available on anti-overriding systems. Their principle is known but little used.

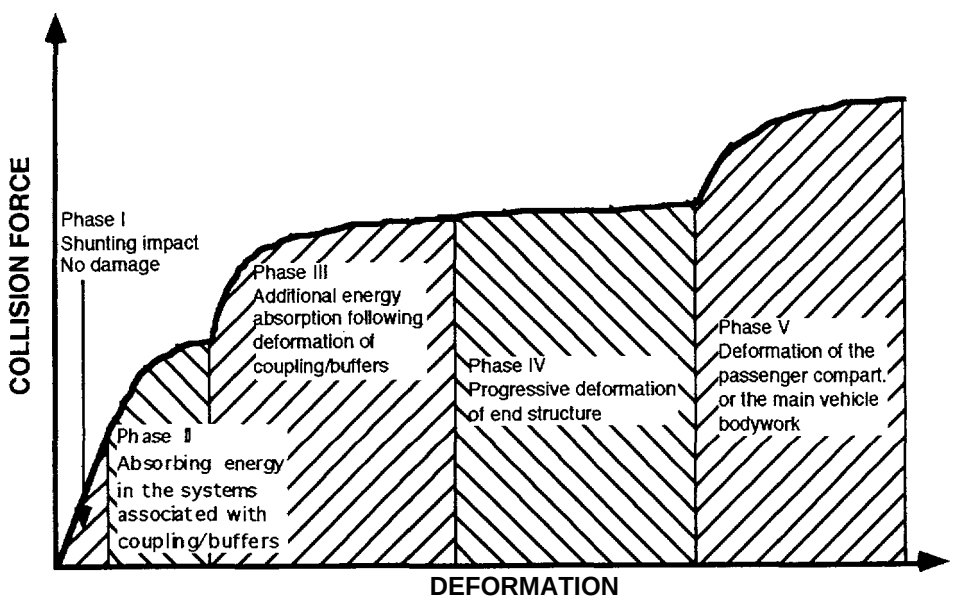


**Figure 2.-** Force displacement curve

## 3. DYNAMIC ANALYSIS OF TRAIN CRASH

The set of tools that have been developed represent a major effort in modem advanced formulations in the area of Dynamic Analysis of Mechanical Systems as applied to impact problems and crashworthiness design of railcar structures. These tools provide a consistent iterative methodology with increasing levels of accuracy and sophistication, including advanced optimization methods which allow the design of optimum characteristics of the different energy absorption devices and anti-climbing systems. The underlying philosophy of these tasks was to provide a set of tools ranging from 1D to 3D rigid body and flexible body models, which are capable of dealing with specific impact and collapse conditions.

Table I summarizes the different software tools, their major features and the scope of applications in the analysis of train collisions and crashworthiness design of rail car structures.

**Table I - Software Tools for Analysis and Design**

| Sub-task | Software Tools | Problem Dim. | Flexibil. effects | Scope of Applications |
|---|---|---|---|---|
| 3.1 | OPT1D | 1D | Rig. Bodies | Dynamic collision of train sets in the longitudinal direction. Optimum design of rakes |
| 3.2 | MB2D | 2D | Rig. Bodies | Overriding phenomena. Optimum design of anti-climbing systems |
| 3.3 | RIFLEX | 2D | Rig. Bodies<br>Flex.Bodies | Dynamic analysis of end underframe structures. Flexibility effects and 2D Plastic hinges |
| 3.4 | COMPAMM<br>(Plastic hinge) | 3D | Rig. Bodies | Dynamic analysis of car extremities. 3D plastic hinges |
| 4.1 | SIM-STAT | 3D | Flex.Bodies | Quasi-static analysis of framework struct. Analysis of collapse mechanisms |
| 4.2 | MBOSS_FLEX | 3 D | Rig. Bodies<br>Flex.Bodies | Dynamic analysis of car extremities. Nonlinear deformations |

In the next sections the different software tools are outlined and the its capabilities and results are assessed.

### 1D AND 2D ANALYSIS AND DESIGN TOOLS

The requirements on the optimum design of impact absorption in frontal collision have been identified. The performance objective is to minimize the maximum accelerations and force levels which occur during the transient response in collisions of train sets represented as ID models of concentrated masses linked by appropriate nonlinear springs.

The optimization procedure integrate different modules in one single software cede OPT ID

- CRASH1D - analysis program for frontal collision of train sets;
- DUALM - optimization program using convex linearization and a penalty method;
- OPT lDM - Driving module to schedule CRASH1D and DUALM during the optimization process and evaluate sensitivities.

The optimization problem to be solved corresponds to minimizing the peak accelerations subject to constraints on allowable deformations ensuring thus designs with minimum survivable passenger space.

Several optimization studies have been carried out for collisions of train sets with and without motor coaches. 1D models for the railcars are represented in figure 3. Different plastic stages have been considered as design variables: Plastic stages of fuse areas, compartment areas and coach fuse areas.

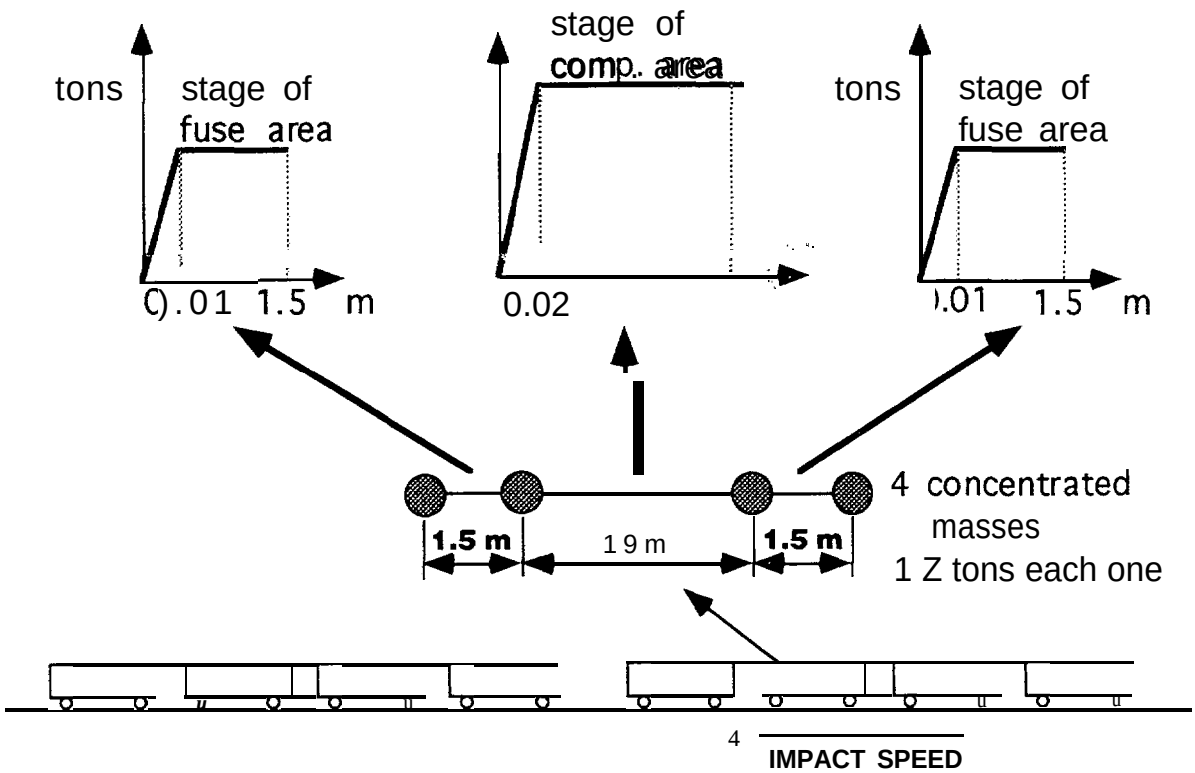


**Figure 3.-** 1D train set models

In 2D formulations the mechanical system is represented by a set of rigid bodies that are connected by kinematic pairs and deformable pairs. A Cartesian coordinate formulation with kinematic constraints was adopted for the analysis model, yielding a set of mixed differential-algebraic equations which has to be integrated in time. A variable order, variable time step with a predictor corrector algorithm is used. The augmented lagrangean formulation which was adopted allows the direct extraction of the reaction forces exerted on the kinematic joints. The baseline analysis module also provides, at each instant of time, position, velocities and" acceleration levels.

2D formulations allow the modeling of rail cars underframes by an assemblage of rigid or flexible bodies with degrees of freedom in the longitudinal and transversal directions and yaw rotational motion. Nonlinear springs and dampers are also included, representing the elastic plastic buckling and collapse behaviors of the relevant rail cars structural parts that are anticipated to undergo large plastic deformation. Theoretical and experimental data are obtained to characterize these actuators. End underfrarne structures have been successfully analyzed with these codes.

The same nonlinear programming method with convex linearization as defined before has been used in the optimization package. Due to the transient nature of impact behavior, a "worst case" approach has been implemented which requires the location of the maximum values of the transient responses. Overriding phenomena was studied and optimized in terms of a set of design variables describing the different plastic stages of railcar structures.

## 3D MODELS

**3D** models are used to assess the overall behavior of car extremities(see figure 4), which are modeled as an assemblage of either rigid bodies or flexible members including material and geometric nonlinear effects. A quasi-static module has also been developed, which has shown to be suitable to predict, in a very efficient manner, possible collapse mechanisms, load carrying capacity and energy absorption levels, allowing crucial decisions to be made with limited design information.

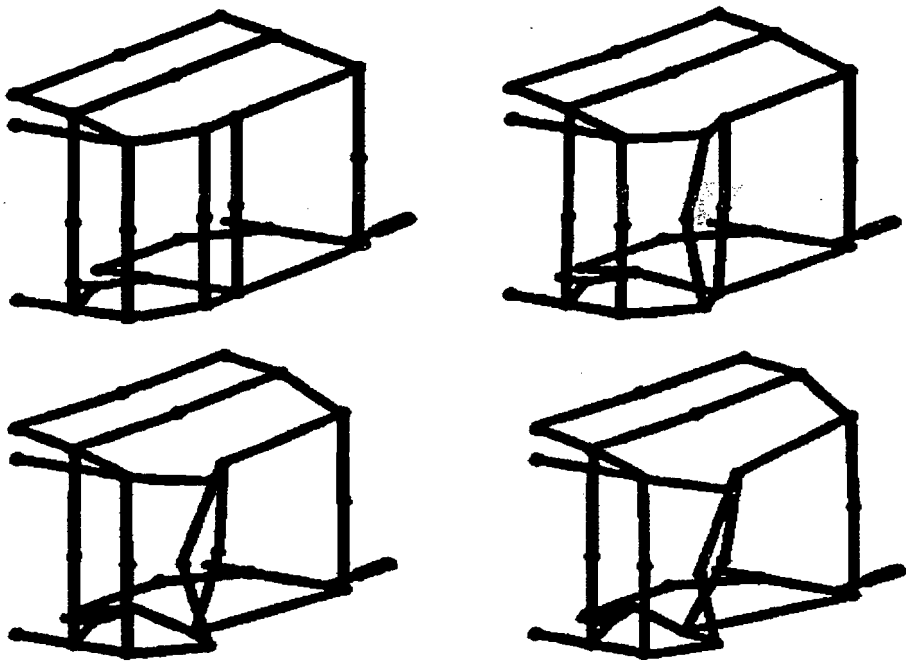

**Figure 4.- 3D** rigid body model

## 4. DESIGN SENSITIVITY ANALYSIS OF LINEAR AND NONLINEAR STRUCTURES

The continuum approach of design sensitivity analysis and the adjoint variable method were used to extend the existent theory to nonlinear structural systems. A unified algorithm permits numerical computation of design sensitivity information for both linear and nonlinear structures. The unified approach is computationally efficient and considers structural design parameters such as thickness and cross-section geometric parameters. Definition of performance measures and constraints, pertinent to structural design engineers, such as compliance, stress, displacement, and eigenvalue is allowed.

The module developed within the project is interfaced with two commercial finite element codes as an add-on capability to replace currently available design practices based on trial and error by providing systematic design information to guide design decisions.

The framework of the design sensitivity analysis code was developed using an object oriented approach and the design sensitivity analysis code was implemented in C++. The framework is general, allowing ease of integration of other finite element codes. Currently both ANSYS and ABAQUS **can be** used to support analysis and design sensitivity analysis.

ASCII interfaces have been defined and implemented to integrate the ADS optimization package with the design sensitivity analysis module. The interfaces permit the execution of the ADS optimization code. Automated module execution is supported by a relational database for dataflow control. Data required for finite element analysis, design sensitivity analysis, and design optimization is handled automatically by the data manager.

A selection of two mathematical optimization algorithms is provided. The control parameters and tolerances are defined by default, but may be modified at user's choice. The performance of the mathematical optimization algorithms was tested on a number of structures of industrial size. The rate of convergence was quite good in general, and improved designs could be obtained after only a few iterations.

A nested control algorithm was implemented, allowing automatic or interactive execution of each of the modules that have been integrated for structural optimization. Design sensitivity analysis may be carried-out at any intermediate design suggested by the optimizer.

The optimization algorithm permits definition of rather general formulations, allowing the selection of individual performances or their combination as design constraints.

## 5. STATIC CRUSH TESTS, DYNAMIC CRASH TESTS

A comprehensive program of static tests was carried out with the objective to initiate a data base system on plastic hinge characteristics of a variety of beam components and to obtain the crush (in terms of load-displacement curves) characteristics of some complex sub-assemblies.

A series of dynamic tests was also carried out on simple components, reduced scale mock-ups and full scale vehicles.

Tubes and beams of different cross section shapes are widely used in railcar vehicles. Past experience shows that free collapse modes in uniaxial bending and the subsequent development of local hinges have a predominant occurrence during crash situations of such structures. The determination of plastic hinge characteristics and the knowledge of the crush behavior of typical components can be estimated by simple empirical methods but requires an extensive experimental verification.

### STATIC TESTS

The objective of the static tests program is the determination of crush and hinge characteristics of typical components of railway end frame components. To obtain these results a series of tests have been carried out on the following components and sub-assemblies:

- 6 different types of carbon steel profiles under different loading conditions;
- 6 substructures using different geometries and different materials under axial crushing;
- Full scale end underframe structure under axial crushing (see figure 5).

In general there is a good correlation between the theoretical calculations carried out with a commercially available Finite Element code and the bending tests of the different beam profiles. In the tests in which the effect of local buckling is important, there are significant differences between the numerical results and the values obtained experimentally. This difference can be corrected by proper mesh refinement.

A data base for the mechanical characteristics of relevant profiles have been established which can be used in the different software tools.

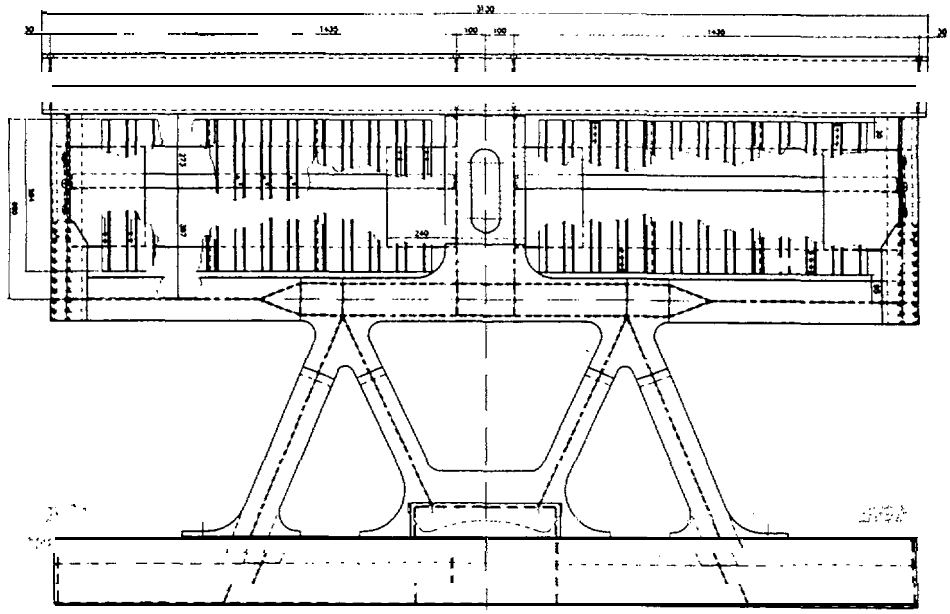

**Figure 5.-** Full scale mock-up of end underfrarne

Results also have provided information about the efficiency of the different components and sub-assemblies for the dissipation of energy in plastic deformation under quasi-static conditions and some insight in the application of similitude techniques for reduced scale models which are used to greater advantage in terms of the costs involved in manufacturing and testing procedures.

DYNAMIC TESTS

The dynamic tests provided a set of consistent experimental results in order to validate the different software tools and assess the validity of the different computer models used in the different design stages. The following tests have been carried out:

- Folding beam under a pendulous impact;
- 4 reduced scale mock-ups of end frames and underframes;
- Full scale stainless steel vehicle against an obstacle;
- Full scale single vehicle against another vehicle (see figure 6);

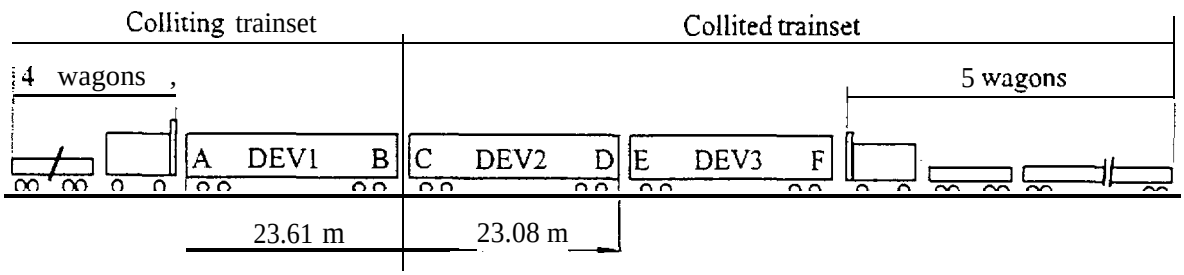


**Figure 6.-** Train configuration

General testing procedures have been successfully implemented allowing the extraction and exploitation of most recorded data. Different results have been presented in terms of accelerations, forces, deflections and strains and provide information about the efficiency of the different components and sub-assemblies for the dissipation of energy in "plastic deformation under dynamic conditions.

## 6. PASSENGER INJURY ASSESSMENT

A computer code and a model to investigate and analyze the kinematic response and the related injury parameters of an occupant under impact conditions has been provided. The parametric investigation utilized a modified version of the SOMTA program in conjunction with a rigid seat model to assess the interactions between the occupant and the railway vehicle seat for various configurations.

The model can be set up to represent one or two rows of a triple seat with up to three occupants on the rear row only. Both conditions of a non-collapsible or a collapsible front seat back can be simulated, using data for the break-over moment characteristics in the latter case. The program allows now four types of occupants, a standard or a non standard human or dummy.

The occupant model considered in the present investigation represented a standard 50th percentile (Part 572) dummy. In addition to the prediction of the secondary impact, the code would allow, if required, the detailed modeling of the seat structure. The secondary impact provides the necessary information about the injuries head, chest or leg segments due to occupant interaction with the front seat back.

A typical occupant simulation is shown in figure 7. The influence of seat back geometry is examined, i.e. contact surfaces, due to secondary contact with the back of the front seat.

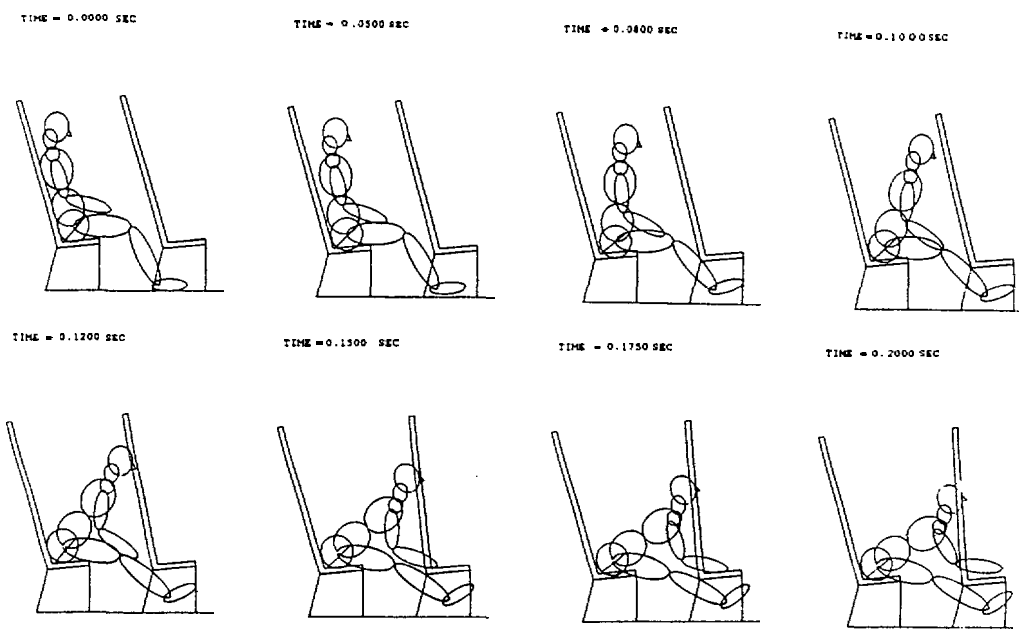


**Figure 7.-** Occupant simulation

## 7. FAIL-SAFE DESIGN OF CARBODY EXTREMITIES

Advanced design of carbody extremities have been carried out. These design efforts have been developed using, in a systematic manner, the available experimental results and the experience and main conclusions obtained from the analysis effort. Exploitation of different end underframe designs have been carried out by incorporating elements with high energy absorbing capabilities in order to meet UIC regulations. The validity of the new designs have been quantified in terms of the energy absorbing capacity of the structures developed.

For crashworthiness structural requirements the two designs have been carried out in such a way that the passenger compartments, in both cases, do not suffer damage.

When defining the general characteristics of the structures the following constraints have been imposed

- The need to have side steps for access to the carat both ends and on both sides of the railcar;
- The need to include a coupling box at the body frame level at both ends (CAF design);

In both designs the structures of the bodies must withstand proof loads as specified in UIC 566:

- Longitudinal compressive e loads:
  - 2000 kN load on buffers;
  - .2000 kN load on central coupler;
  - -500 kN diagonal load on buffers;
  - -400 kN load, 350 mm above the buffer level;
  - -300 kN load at the windows sill level;
  - -330 kN lad at the cantrail level.
- Plastic stage:
  - 2500 kN carbody extremity
  - -3500 kN passenger compartment
- Enerag absorption:
  - -1 MJ for carbody extremity, for 1m deform.;
  - -.2 MJ with overclimbing;
- Total crush displacement (function of the impact speed) from 350 mm to 1000 mm.

Figure 8 illustrate an initial design were a mechanism of two successive energy absorption phases is proposed.

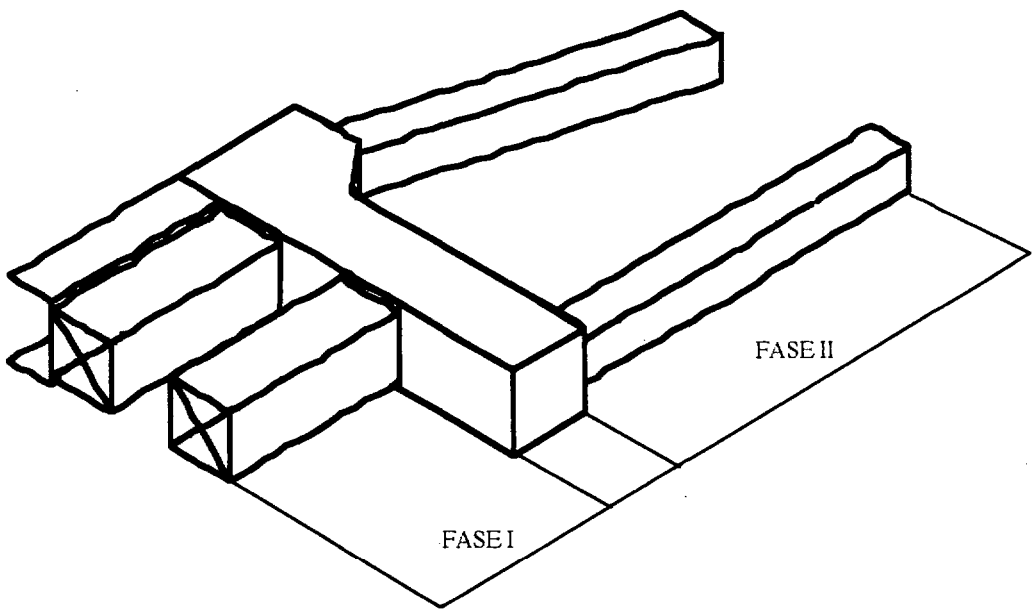


**Figure 8.-** CAF design (half structure)

In both cases the different software tools were used as appropriate and the different service and impact loads, as well as the proposed mechanisms of deformation have been validated.

Throughout the development of this task, a design procedure has been established, based on tests and on the combination of calculations made, both with the tools developed within the project and with commercial codes for calculation using the Finite Element Method.

The use of this procedure has made it possible to dimension the essential elements of a car structure, fulfilling the foreseen design specifications. Moreover, it has been proven the applicability of the different design tools now available for the optimization of rail car structures' behavior under impact conditions.

The need for high calculation times has been observed for the performance of simulations with both RIFLEX and COMPAMM and MBOSS-FLEX, which, to a certain extent, slows down the initial design phase where a large number of possible solutions to the problem have to be studied. However the typical execution times for such programs is well below those required for standard linear and nonlinear finite element analysis.

## 8. OPTIMAL DESIGN OF CARBODY EXTREMITIES

The SOREFAME proposed structure of the car extremity was modeled with PATRAN and analyzed with ABAQUS. The model contains 2769 STR13 triangular shell elements corresponding to 8367 degrees of freedom. For optimization purposes and based on technological reasons the structure was devided into nine components with variable thickness during the optimization procedure. These components are depicted in figure 9.

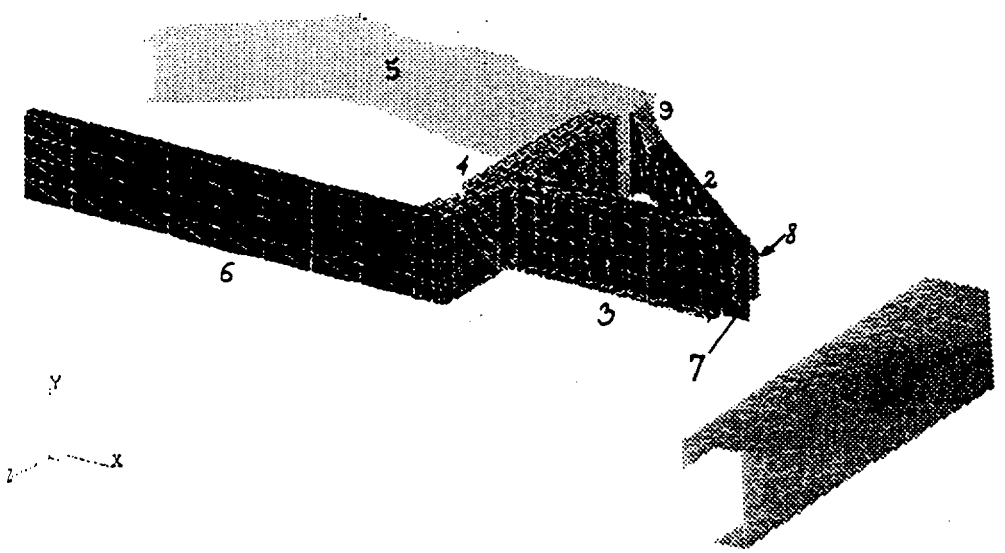


**Figure 9.-** Geometric components for optimization

The optimization problem was defined as a compliance minimization problem subject to specific allowable stress levels to guarantee a desirable deformation sequence (groups 3, 5, 6 and 8). The stresses were also constrained tacking into account the yield stress levels and the safety factor specified by SOREFAME.

The optimum structure was found after 11 iterations resulting in thickness increases in groups 4 and 5. This results indicate that those components must remain rigid during structural collapse. Since the deformation occurs mainly within the plastic range, the results obtained must be looked at as only a demonstration of the optimization capabilities of the software as applied to service loads alone.

A nonlinear design sensitivity analysis has also been carried out with a much coarser finite element representation of the structure (2768 ABAQUS shell elements S3R).

Development of design capabilities for geometric nonlinearity and plasticity is proved as necessary. It was demonstrated the feasibility of the extension of the system to carry out design sensitivity analysis of geometric nonlinear behavior.

## 8. CONCLUSIONS

Taking the state-of-the-art in the study and development of impact-resistant rail cars as a starting point and having carried out a characterization of the typical accidents in the field of rail passenger transport, a working methodology and a series of calculation tools have been developed which allows an appropriate design of the structure to be made, taking the performance which is required from it into account.

Throughout the project, both the qualitative and quantitative behavior which would be demandable from the structures of cars intended for passenger transport has been established.

At the same time, calculation tools for both 2-D and 3-D structures have been developed with the aim of speeding up the design phase in which the amount of calculations is quite considerable. These tools have been extremely useful for executing the initial design stages but not for carrying out the detailed design, due to the great simplifications on which they are based in order to generate the calculation models.

A good correlation has been observed between the results obtained in the structure's simple components and the calculations of these carried out using standard nonlinear Finite Elements Methods. Moreover, a good correlation between the results of the complete structures by different tools developed in the project has been observed.

The calculation tools that have been developed have considerably reduced the time for preparing the calculation models, compared to the commercial tools based on the Finite Elements Method. Further efforts to improve the calculation speed of these tools is still desirable.

Moreover, it should be pointed out that the results obtained with these tools have entailed the use of very simplified models (although they have been based on results obtained from Finite Elements calculations and tests) and therefore their results would only be acceptable within the initial phase of the structure's development. The concept of crushable elements, as explained earlier on, show potentialities to be explored.

In order to optimize the costs related to the development of the train structure, and bearing in mind that the design methodology proposed requires an iterative process, it would be recommendable to carry out an exhaustive study of the structure's simple elements, even by means of tests, as it would be more likely to arrive at an acceptable final solution in this way. Therefore, the final and most expensive phase of the methodology presented would only have to be carried out once.

Further studies are necessary to assess trainset collisions, including rake instabilities and taking into consideration that for many years to come, new crashworthy rakes can collide *with* exhisting train rakes. Overriding phenomena and anti climbing devices is also an important subject to be addressed in a systematic manner.

The different configurations of carbody extremities that have been exploited under this project, particularly new end underframe designs, show that promising improvements can be obtained towards an efficient crashworthiness behavior of carshell structures.

## ACKNOWLEDGMENT

This paper presents a synthesis of the results of the BRITE /EURAM 3385-89 Project "Advanced Design of Crash Fail-Safe Train Structures under Service and Impact Conditions", contract no BREU -0362. This project which started in March 1991 is funded through a 58% partial contri bution from the Directorate General for Science, Research and Development of the Commission of the European Communities and another 42% contribution from the industrial partners in the project: SOREFAME (P), GEC ALSTHOM (F), CAF (S), CIC (UK) and CP (P). The remaining partners, 1ST (P) and UVHC (F), participated on a marginal costs basis.

## REFERENCES

[AMB 92] Ambrosio, J.A.C., and Nikravesh, P.E. "Elastic-Plastic Deformation In Multi body Dynamics", *Nonlinear Dynamics,* **3, 85-104,** 1992.

[ANC 92] Anceau, J. H., Drazetic, P. and Ravalard, I. "Plastic Hinges Behaviour in the Multi body Systems", *Mécanique Matériaux Électricité,* no 444, France, 1992.

[DAC 93] Dacheux F., Développement d'une technique de similitude indirecte sur modèles réduits: application á l'étude du comportment en collision des véhicules de transport guidés. These de doctorat en Genie Mécanique, Université de Valenciennes et du Hainaut cambrésis.

[DAC 91] Dacheux, F., Drazetic, P., Marrisal, A. , and Ravalard, Y. (1991) "Impact Behavior of Structures", in *Proc. of Int. Conf. of Nonlinear Engineering Computations,* Swansea, U. K., September 16-20.

[DIA 93] Dias J.P. and Pereira M. S., 1993, Analysis and Design for Vehicles Crashworthiness, *Proc. International Symposium on Technological Innovation in Guided Transports,* Line, France.

[DIA 94] J. Dias and M. S. Pereira, "Crashworthiness Optimization of Vehicles", I. J. Vehicle Design, Vol. 15 no. 3/4, 1994.

[DRA90] Drazetic P., Comportment au choc des véhicules guidés, contribution à la validation de modèles numériques par confrontation avec les résultats expérimentaux. Thèse de doctorat en Génie Mécanique, Unviersité de Valenciennes et du Hainaut Cambrésis.

[DRA 93] Drazetic P., Markiewicz, Ravalard, Y., "Applications of Kinematic ModeIs to Compression and Bending in Simplified Crash Calculations", Int. Journal Mech, Sci., Vol. 35, N" 3/4, pp179-191, 1993.

[DRA 94] Drazetic P., Dacheux F., Marguet B., Ravalard, Y., Applying non Direct Similitude Technique to the Dynamic Bending Collapse of Rectangular Section Tubes, Int. Journal of Impact Engng., Vol. 15, N" 6, pp. 797-814, 1994.

[DRA 95] Drazetic P., Tassin R., RavalardY., Aided Tool for Rigid Multibody Modelling of Impact Structures,. Int. Journal for Computer-Aided Engineering and Software, Vol. 12, N*1, pp. 21-34, 1995.

[CHO 87b] Choi, K. K., Santos, J. L. T., "Design Sensitivity Analysis of Nonlinear Structural Systems Part 1: Theory ".I. J. Num. Meth. Engng, 24, 1987, pp2039-2055.

[CHO 88] Choi, K. K., Santos, J. L.T., "Design Sensitivity Analysis of Nonlinear Structural Systems Part II: Numerical Algorithm".I. J. Num. Meth. Engng, 26, 1988, pp2097-21 14.

[CRU 94] Manuel Cruz and M.S. Pereira, "Crashworthiness Analysis and Design of Trains", International Symposium on Advanced Materials for Lightweight Structures'94, ESA-ESTEC, Holand 1994.

[FLE 861 Fleury C., Braibant V., "Structural optimization: a new dual method using. mixed variables", Int. J. Numerical Methods in Engineering, Vol. 23, pp. 409-428, 1986.

[JIM 89] Jimenz, J. M., Avello, A., Garcia-Alonso, A., Garcia de Jalon, J., "COMPAMM- A Simple and Efficient ode for Kinematic and Dynamic Numerical Simulation of 3D Multi body Systems with Realistic Graphics", in Multibody Systems Hanbook, ed. by W. Schielen, Springer Verlag, 1989.

[MAR 93] Marissal A., Drazetic P., Marguet B., Ravalard Y. and Lagneau H., 1993, Two-dimensional Collision in Railways-application for Climbing Risks, *Proc. International Symposium on Technological Innovation in Guided Transports,* Line, France.

[MAR 94] Markiewicz E., Contribution au développement d'une méthodologie simplifiée d'aide au design collision des véhicules de transport pendant la phase de préconception: Introduction du concept de super éléments de pliage, Thése de doctarat, Université de Valenciennes, 1994.

[ORE 91a] Question B 165, Résistance dunamique aus impacts frontaux des postes de condduites, Office de Recherches et d'Essais de l'Union International des Chemin de Fer, Utrecht, The Netherlands, 1991.

[ORE 91b] Description technique de la conception de vehicules, Question ORE B165, rapport n" 8, Utrecht, 1991.

[OUD 92] Oudshoom, A., "Optimisation sous constraints de structures d'avant-projets", Proceeding "Transport 1992+", CSME forum, Concordia University Montréal, vol. 3, pp. 810-816.

[OUD 92] Oudshoorn, A., "Contribution à l'optimisation des structures mécaniques sous contraintes. Application aux structures des véhicules de transports guidés", Thèse de Doctorat, Université de Valenciennes.

[PER 91] Pereira, M. S. , and Proença, P. L. "Dynamic Analysis of Spahal Flexible Multibody Systems Using Joint Coordinates", *Int. J. Num. Meth. in Engng.*, 32, 1799-1812, 1991.

[PER 94] Pereira, M.S. , Drazetic, P. , and Ravalard , Y. (1993) "An Hybrid Method For Impact Analysis of Rigid-Flexible Structural Systems Undergoing Gross Motion", submitted to *J. Impact Engng.*

[PER 95] M. S. Pereira and J. A. C. Ambrósio, " Design Methodologies for Train Crashworthiness Using Multibody Dynamics", International Crashworthiness and Design '95 Symposium, 3-4 May, 1995, Université de Valenciennes.