ENHANCED SEAT BELT MODELLING PROCESS TO IMPROVE PREDICTIVE ACCURACY OF DUMMY RESPONSES IN FRONTAL IMPACT

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ABSTRACT

Computer simulations are a standard tool for improving vehicle safety. In these simulations, predictions about dummy responses and injury assessment values can be made. For accurate predictions, the behaviour of the retractor as a major part of the seatbelt system has to be known. Tests are needed to generate this knowledge and incorporate it into a simulation model. Standard sled tests are too expensive and generally have too much deviation to be a useful correlation environment. Component tests are of limited use due of the lack of interaction, or the coupling between the different crash phases. Subcomponent tests are only useful if a robust simulation model already exists. Furthermore, a model structure is needed which reflects all main effects of the retractor in a time independent way.

Thus, there are two needs for an enhanced modelling process: A correlation test device as well as a model concept which reflects the interaction in a simple and robust way.

This paper demonstrates a new process on how a retractor model can be correlated in different solvers with a component test, within the typical working points of a retractor. The improved process is based on a new easy test assembly for retractors (ETAR) and on a general model structure (GMS) for the retractor models. The new component test assembly reflects the three phases of pretensioning, coupling and load limiting of a frontal crash without the need of a sled and/or dummy. Furthermore, for the correlation of retractor models in different solver codes, ETAR allows to generate test data in a fast and simple way with low deviation. The GMS implements all the main functionalities of a retractor and due to the GMS, the tuning of the models is easily transformed into other solver codes, commonly used for crash simulations.

Correlations between test and simulation for different load-cases and different retractors in different solvers demonstrates the applicability of ETAR and GMS for an improved retractor modelling.

INTRODUCTION

A good and reliable crash performance in frontal impact tests, for both homologation and for consumer ratings, is a major prerequisite in car design. During the process of system layout for frontal impact, all parts of the restraint system have to be adapted to the particular vehicle environment. This is done by physical crash tests and by computer simulations simultaneously. In the early phase of the development, the tests are performed to verify the simulated results, and the simulation models are used to optimize the parameters. Thus, simulation models of the restraint system must be available and reliable.

The seat belt is a fundamental part of the occupant restraint system. Modern seat belts have a pyrotechnical pretensioner unit to reduce belt slack and tighten the occupant to the car in the first milliseconds of a crash. The pretensioner device can act at the retractor, at the buckle, or at the anchor plate. Combinations of two pretensioners are possible. In the phase of maximum occupant loading, after about 50 ms, a load limiter keeps the belt force at a constant level, which is - depending on the specific car and seating position - between 3 kN and 6 kN.

Crash tests do not need to be performed in a real physical environment. Crash tests can be done by physical crash tests and by computer simulations. The physical tests are time-consuming and the information is limited to the amount and kind of sensors. Computer simulations are an important tool to overcome these deficits. In such simulations, numerical models calculate the behaviour of the dummy during the frontal crash. This kind of simulation is also called system simulation or occupant protection simulation. Injury assessment values as well as forces in the restraint system are generated by such models. For system simulation models, the predictability of the whole system depends on the accuracy of every subcomponent. Without a validated retractor model, a predictive crash occupant protection simulation model will not be possible.

Ideally, these system simulation models should be predictive for different load cases. However, different load cases will in turn change the working point of the retractor. Consequently, the retractor model is required to be predictive for different working points. If a model is predictive for different load cases, the model will be called robust.

So, the predictive accuracy of dummy responses in such system simulations depends not only on the accuracy of the dummy model, but also on the accuracy of the interaction of components. This generates the apparent need for a robust retractor simulation model that has to be validated for different working points. In turn, tests with different working points are needed to correlate the retractor model.

The retractor itself is a component with different functional subcomponents. These are in interaction with other subcomponents and components outside of the retractor. In general, these subcomponents cannot be validated separately for a robust retractor model, due to the nonlinear interaction in the system.

The different vehicle manufacturers use different numerical solver codes in their vehicle development processes. The chosen solver has an influence on how different effects can be implemented into the model. Thus, the solver has an influence on the model structure and due to this, also on the approach and the effort associated with the correlation.

For correlations with different working points, different model structures for different solvers are needed for predictive component models.

The more effects and more load cases which should be reflected by a model will raise the amount of needed tests for the correlation. To validate retractor models, tests in a simplified environment are performed. Classically, a sled test according to ECE-R 16 /1/ using a Hybrid III 50th-percentile dummy /2/ is performed, a corresponding simulation model is set up and parameters such as belt forces, webbing pay-in by pretensioning and pay-out by load limiting are adjusted. The main drawback is that the validation has to be done separately for each solver, especially as each solver has its own dummy models.

The usage of frontal crash simulation to improve the predictive accuracy of dummy response is limited by the performance of the simulation models of the subcomponents (e.g. retractor). Thus, to generate a robust and reliable retractor model, in the classical correlation manner, a substantially high correlation effort is required. This paper presents a process showing how robust and reliable models can be correlated, in different solvers, in a fast and effective manner.

CORRELATION PROCESS

Figure 1 shows the new fundamental correlation process. The process for the validation is the same for all solvers. Furthermore, the functionalities of the test rig as well as for the component model should be the same for all solvers. This is of fundamental importance to minimize the effort for correlating the same models in different solver codes. The model is correlated for different load cases (LC) in an easy test assembly (ETA) model environment.

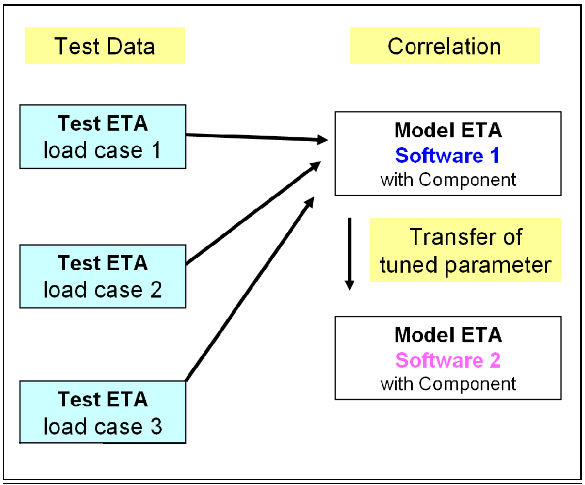

Figure 1. Principle correlation process for different solver.

Once a correlation in one solver code is done, the tuned characteristics of one model can used for the same model in the other solver codes. Due to small solver related differences in the subroutines as well as the available sensors and functions in the different codes, the simulation results are bound not to be exactly the same. However, if all physical parameters are the same, the results of the different solvers should correlate well to each other.

There are two principle ways how a component model can be generated. The first is a black box model in which the behaviour of the subcomponents are not reflected. For such a model of a retractor, only the force and belt pull out (pull in) behaviour at the retractor have to be correlated for the different load cases. In an effect based model, the functional subcomponents are reflected. This model is also called white box model, in which the origin of the component behaviour is allowed to be analysed. Due to the interaction in a system, every subcomponent of such a model has to be validated for different load cases. In general, the model structure of a white box model is more complex than that of a black box model, but a white box model can also be used for gaining an understanding of effects and subcomponent analysis. Due to this, a white box structure is chosen. An additional benefit of this kind of structure is the possibility to use the already available subcomponent characteristics.

ETAR

Numerous tests exist for the validation of retractors and their functionalities. These tests are made for a subcomponent of the retractor or for the restraint system. The subcomponent tests are not useful because they do not reflect the interaction of the individual subcomponents with each other. The restraint system tests have their focus on the whole restraint system and do not concentrate on the component. In general the restraint test rigs have more data variation and are more time-consuming. In the following, we will describe the development of a fast and repeatable component test method which can substitute a sled test for retractor validation and of which a CAE model can easily be build up in each solver /3/.

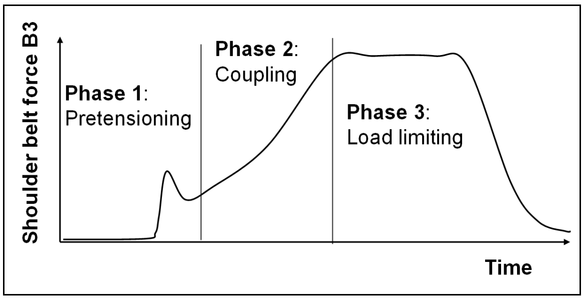

Figure 2. Schematic illustration of the 3 phases of a sled test.

The requirements to a correlation test for retractor models that are to be implemented in system simulation model are different to those tests, which are designed for evaluating injury assessment values. For example, although the easy test assembly for retractors (ETAR) has to reflect all important crash phases of the retractor (Figure 2), thus maintain resemblance to the actual working points of the retractor model, the assembly should also have low variation, should not be time-consuming, should have only a few parameters and should be able to be modelled in all relevant solvers in a simple manner. The geometry of the test rig can be much simpler than the geometry of a belt restraint system. However, it is essential that the working points of the retractor in such an easy test assembly must be in the same range as in real crashes test environments.

In order to fit these requirements, ETAR was built in two steps. In the first step, the requirements to the pretensioner performance were defined, and in a second step the coupling and load limiting phases were added.

It is assumed that a system with a damping function, a dynamic mass and an elasticity (two linear springs) can lead to an environment with a realistic retractor working point for the pretensioning, see Figure 3. This subcomponent of ETAR is called ETAR1. The fundamental initial parameters are shown in Figure 3b.

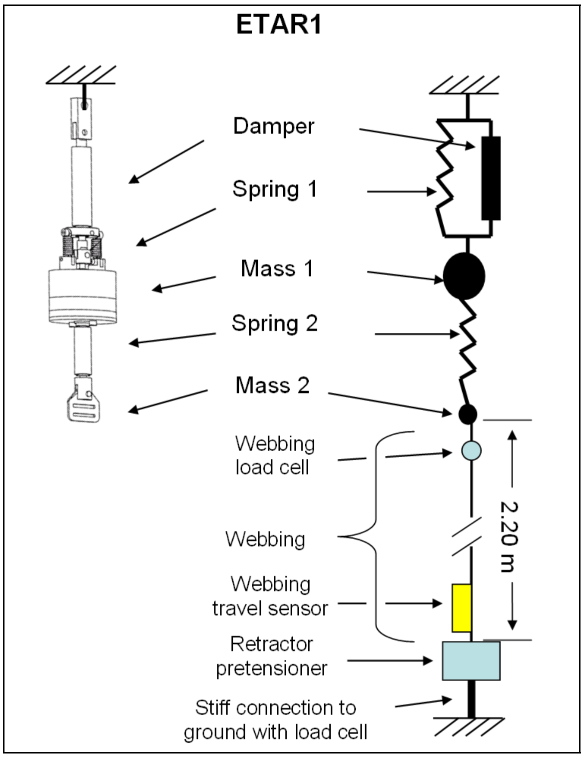

Figure 3. Basic hardware ETAR set up for pretensioning phase.

ETAR1 is vertically orientated at the top of ETAR and connected to the retractor pretensioner by 2.20 m of webbing, as shown in Figure 4a. A force measurement is provided at the retractor fixation point in addition to a webbing load cell at the ETAR1 end of the webbing. A start set of masses, spring and damper characteristics was obtained by simulation.

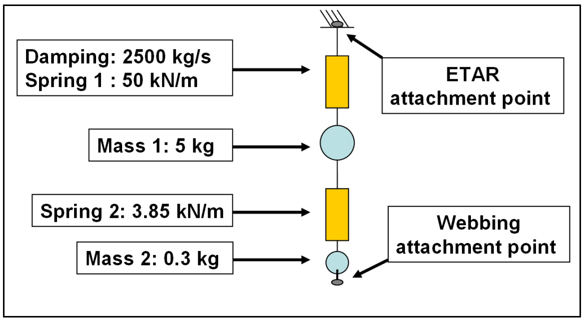

Figure3b. Parameter for the basic ETAR set up for pretensioning phase.

In order to cover a wider area around the working point of the retractor, two additional load cases were introduced. Theses different working points should reflect the adaptive behaviour of the retractor for different preloads. The first is a "slack" load case, representing car environments with yielding parts, such as seat belt buckle fixation, webbing being routed over seat cushions, etc. In these environments, more pretensioning distance is achieved. It is known from pre-tests that a very low preload (below 20 N) yields in less repeatability. For this reason, a low preload of around 50 N has to be applied, therefore Spring 2 must be substituted by a softer one. The second additional load case is performed with a high preload (~ 400 N), which accounts for load cases with a late firing of the pretensioner, when the dummy's forward displacement is already loading the belt system. Again Spring 2 has to be replaced, this time by a stiffer one.

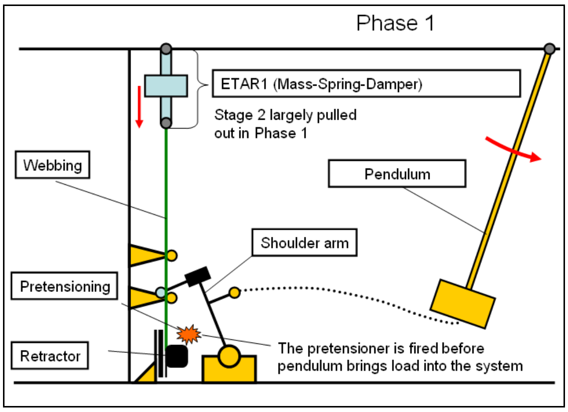

Figure 4a. ETAR set up for webbing pull in while pretensioning. No influence of shoulder arm on pretensioning.

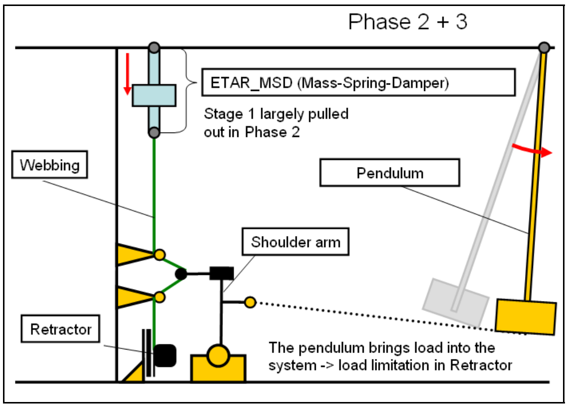

Figure 4b. ETAR set up for webbing pull out after pretensioning.

In a second step, a device to emulate phases 2 & 3 (ETAR2) is added. It is set up in such a way that the events in phase 1 is not disturbed by it. A shoulder arm, accelerated via a string by a pendulum is pulling out webbing between ETAR1 and the retractor. Due to the geometry of ETAR2 the pull out velocity is similar to that in a sled test as opposed to that in a direct pull of the pendulum.

A high repeatability compared with common system test like AK static or ECE R16 sled tests /1/ can be achieved, caused by only a few parameters in the comparatively simple geometry.

In Figure 5, the force at the retractor for 3 identical tests are shown. The force and the pull in starts before 0 ms because the data acquisition was triggered by the pendulum, which will trigger before 0 ms. In the beginning at 2 ms and 10 ms two distinct pretensioner peaks can be identified.

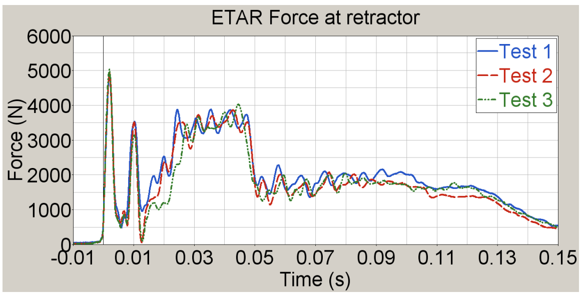

Figure 5. Retractor force test data versus time; three ETAR test repetitions.

After the pretensioning, the force rises up to the first load limiter level. This coupling phase will be due to the impact of the shoulder arm in the belt system (Figure 4b). At 25 ms the load limiter is limiting the force on a level of 3500 N. The force drops down at 45 ms is due to a switching load limiter which is switched to a second, lower load limiter level.

In Figure 6 the belt pull outs at the retractor for the same 3 identical tests as in Figure 5 are shown. In the beginning a belt pull in (negative belt pull out) up to 150 mm is reached. Thereafter, during the coupling phase of ETAR, the constant level of belt pull out is reached. The belt pull out for the load limiting starts at 25 ms and stops at 95 ms. During load limiting, more than 500 mm webbing is pulled out of the retractor.

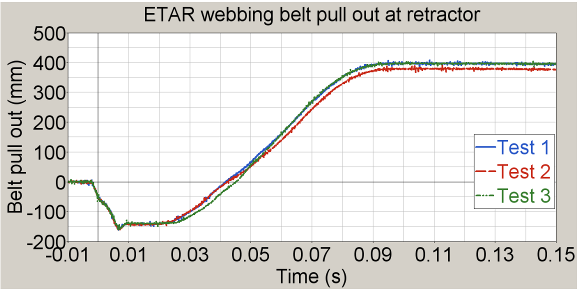

Figure 6. Retractor webbing pull out test data versus time; three ETAR test repetitions.

These tests show the capability of ETAR to detect the force and belt pull out of the retractor for all three phases of a crash.

GENERAL MODEL STRUCTURE

This chapter presents an overview over the general model structure (GMS) of the retractor model and the working principles of the GMS. The GMS retractor simulation model is implemented in several solver codes, such as Madymo, LS-Dyna, PAM-Crash, Abaqus. Although the model structure and characteristics are implemented in an identical manner in all solvers, not all functionalities, settings and switching systems can be implemented in an identical manner. This is due to the varying capabilities of the different solver codes.

The retractor simulation model consists of twelve sequentially arranged translational joints. This GMS is invariant for all retractor simulation models and is referred to as the “chain-of-joints” (Figure 8). Each joint respectively represents some single, designated functionality of a physical retractor component (i.e. pretensioner, torsion bar, shear pins, etc.), or some characteristic effect (film spool, locking, etc.), or (pre-) loading conditions of a retractor. Each joint is modelled as a spring-damper sub-system.

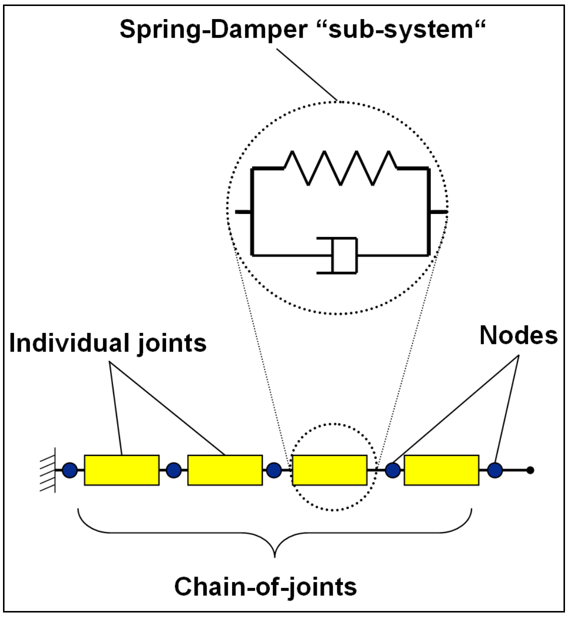

Figure 7. General model structure (GMS).

For the individual solvers, the joint types and material types are specifically selected in order to model the appropriate behaviour. Thereby, designated loading / unloading characteristics, hysteresis models and damping behaviours are specified for each joint. These functionalities are reserved for all joints but not necessarily always implemented. Finite lumped masses are implemented on the node between any two adjacent joints.

Generally, the one end of the chain-of-joints is to be attached to the vehicle, the other end to the webbing. This defined structure and sequence of the joints in the chain-of-joints is invariant.

All of the joints are always implemented for all retractor models. Not all joints are always active at any given point in time and/or are used in all retractor models. The deactivated joints are set as rigid. With regard to the FE-solver codes (LS-Dyna, PAM-Crash, Abaqus), it has to be noted that the joints are set as “rigid” by assigning a significantly high, yet finite, spring stiffness function to the spring component of the joint. Strictly speaking, such joints do have some remainder of elasticity, which however is considered insignificantly small such that these joints may essentially be considered to be “rigid”. Table 1 gives an overview of the individual functionalities and effects that are reserved for the individual joints.

Any specific retractor functionality is implemented into the corresponding retractor joint in the model in terms of characteristic spring stiffness function, damping function and a lumped mass. These parameters / characteristics may be given as scalars, linear or non-linear functions and vary depending on the retractor model and the individual functionalities. The spring stiffness characteristics are generally given as linear / non-linear functions with hysteresis. The reserve joints can be used for necessary system tuning. This can be useful if additional elasticity form the attachment point in the vehicle or of the webbing or additional masses in the belt system, like load cells, should be reflected.

Joint	Function / Characteristic
Bolt	Retractor position in vehicle no characteristic
Frame	Deformation characteristics of frame
Spring	Preload conditions, retraction spring and pre-pretensioner
Stroke	Pretensioning of retractor
Locking	Locking travel of the lock dog Remainder of pressure in pipe
Shearpin	Shearing off of the shear pins
Load Limiter 1 (LL_1)	First stage of the load limiting
Load Limiter 2 (LL_2)	Second stage of the load limiting
Spindle	Inertial effects of the spindle
Filmspool	Film-spool effect
Reserve 1	Reserved joint for future use
Reserve 2	Reserved joint for future use May be used for system tuning

Table 1. Overview of functionalities and effects of the different joints of the chain-of-joints.

In order to model physical retractor behaviour, a switching system is implemented which activates / deactivates certain joints. Thereby the various retractor functionalities are activated / deactivated, as required. Various sensors are implemented reacting to displacements, velocities, accelerations, forces as well as user defined times to fire. Depending on the load case dynamics and the physical type of retractor that is being modelled, the various implemented sensors may or may not be triggered during the sequence of events, i.e. not all sensors must be triggered for a retractor to function normally. Time dependent switches are implemented as a back-up trigger. This can be used in the case the usual sensors are not available in the used solver version, the usual sensoring of the switching fails, or to specifically end some functionality at some user defined time.

Apart from pretensioning and a constant load limiter, a non-constant load limiter can also be a functional component of a retractor. The non-constant load limiting can be achieved by switching from a first load limiter level to a second load limiter level. This function is called Load Limiter Adaptive (LLA).

With predefined outputs of the joint displacement the functionality of the model can be easily controlled. In Figure 8, an example of the displacement of the individual joints of the chain is shown. A pre-simulation is used to implement a defined preload into the system. The retractor is able to pull in webbing (Stroke) and switch the load limiter level.

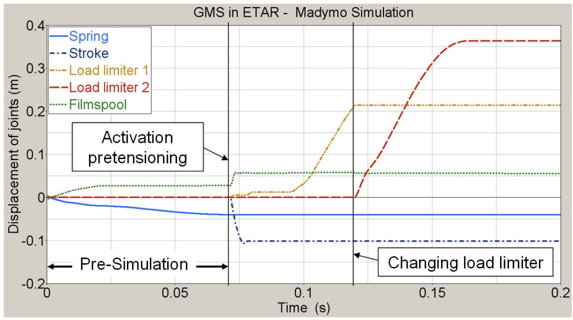

Figure 8. Example of joint displacement of the GMS in ETAR with pretensioning and adaptive load limiting (LLA).

In the pre-simulation, elasticity of the film-spool will be eliminated. Using a user defined time, the spring joint is locked by a time sensor, whereby the pre-simulation is ended. During subsequent pretensioning, the corresponding pretensioner joint will cause the specific elongation of the first load limiter joint as well as the film-spool joint, by which the elasticity of the film-spool is eliminated. The LLA is fired by a time sensor whereby the second load limiter joint is activated, which becomes the load carrying / dissipating path since the second load limiter has a lower load level than the first.

Using such a 1-D white box model, a GMS for all typical retractor types is available. In the next step the correlation results for the GMS in ETAR will be shown.

CORRELATION RESULTS

The correlation of the general structure can be done in different solvers. The starting tuning configuration is given by component tests and physical component parameters. Model parameters which are not known are the main tuning parameters. The main objective is to obtain a robustly correlated simulation model of the retractor component. Beside the damping, masses and spring loadings, the hysteresis is important for the energy absorption and for the damping of oscillations.

In Figures 9a and 9b, a retractor without pretensining and with a constant load limiter is correlated in Madymo. Two different configurations are shown. The difference is the remaining webbing (RW) on the spindle. The RW is the webbing which is wound on the spindle and has an influence on the force levels and belt pull out behaviour of a retractor.

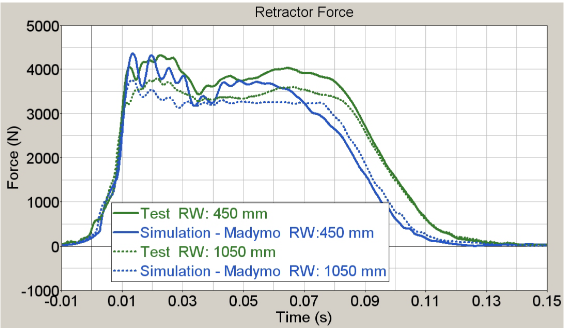

Figure 9a. Force versus time ETAR correlation plot of a retractor with two different remaining webbing (RW) on spindle.

Test and simulated forces of ETAR are shown in Figure 9a. The force level of the retractor with a RW of 450 mm is higher in test, as well as in simulation, than that for the retractor with a RW of 1050 mm, as it could be expected. The coupling phase is identical. In Figure 9b, test and simulated belt pull outs are shown. The belt output of the retractor with a RW of 450 mm is lower in test, as well as in simulation, than that for the retractor with a RW of 1050 mm.

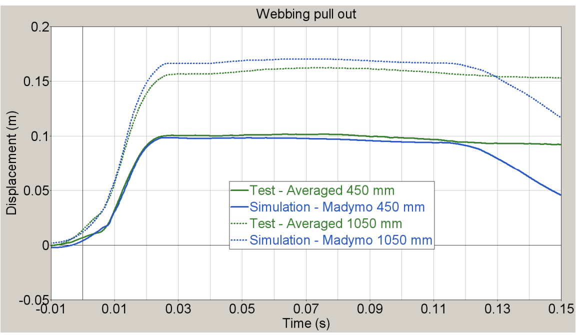

Figure 9b. Webbing pull out versus time ETAR correlation plot of a retractor with two different remaining webbing (RW) on spindle.

Figures 10a and 10b show a retractor with pretensioning and with an adaptive load limiter, as correlated in LS-Dyna. Two different preload conditions are shown.

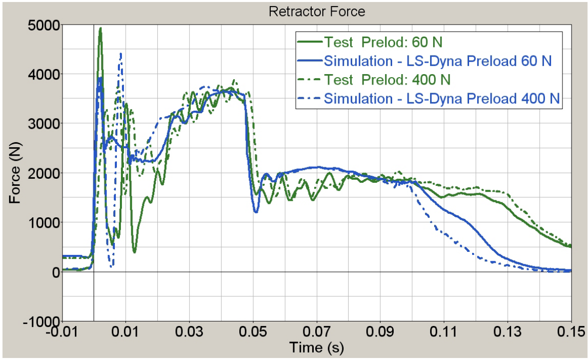

Figure 10a. Force versus time ETAR correlation plot of a retractor with two different preloads. Retractor with pretensioning and adaptive load limiter (LLA).

Figure 10a shows the test and simulated retractor forces in ETAR. The force level in the coupling phase of the retractor with a preload of 60 N is lower in test, as well as in simulation, than that for the test with a preload of 400 N. The force levels during load limiting are identical. The earlier reduction of force levels from 100 ms onwards can be explained by the hysteresis function.

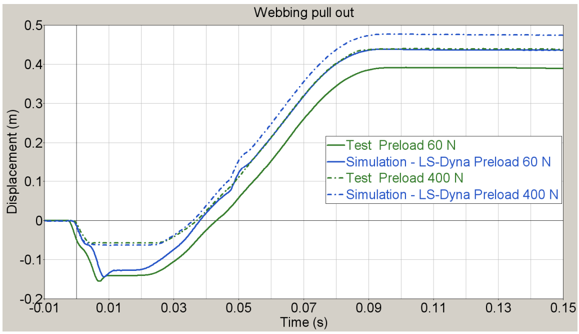

Figure 10b. Webbing pull out versus time ETAR correlation plot of a retractor with two different preloads. Retractor with pretensioning and adaptive load limiter (LLA).

Figure 12 shows test and simulated belt pull out. The pull in of webbing during pretensioning is higher in the lower preload LC. The load limiting starts earlier in the higher preload LC.

The Figures 11a and 11b show the simulation results of a retractor with pretensioning and with an adaptive load limiter for different solver codes with a

150 N preload in ETAR. Modifications in the switching, as described previously, have to be done. The force levels as well as belt pull outs signals a significantly comparable. The model structure is also the same for all models in all solver codes.

The observed differences are caused by differences in the subroutines as well as the available sensors and functions in the different solver codes. Thus, the simulation results are bound not to be exactly the same. These differences between the different solver codes are subject to further evaluations /4/.

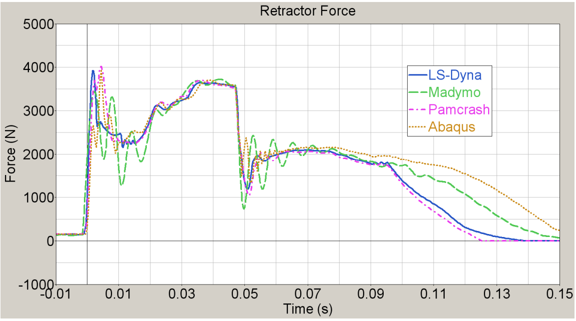

Figure 11a. Comparison of force versus time simulation results of different solvers.

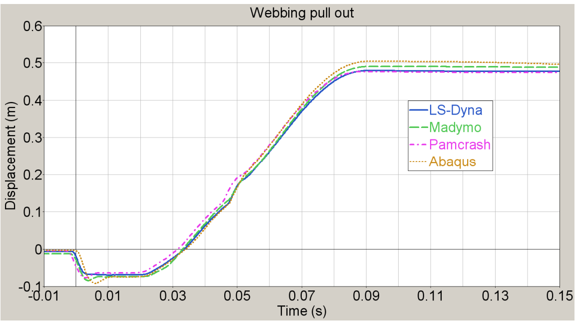

Figure 11b. Comparison of force versus time simulation results of different solver codes.

The correlation results of the different retractors in different preload configurations and in different solvers show the capability of the new validation procedure.

SUMMARY

An enhanced seat belt modelling process which can be used to improve the predictive accuracy the subcomponent model using an easy test assembly for Retractors (ETAR) in combination with a general model structure (GMS) for the retractor simulation models has been discussed.

Correlation test data for all frontal crash phases, relevant for occupant protection, can be generated using ETAR. Furthermore, ETAR can be modelled nearly identically in the standard crash solver codes. With this test and simulation environment, a robust correlation can be done and the correlated functions of the general model structure (GMS) are exchangeable between different solver codes.

Correlation results between test and simulation for different load cases and different retractors models in different solver codes demonstrates the applicability of ETAR and GMS for an improved retractor modelling approach.

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/2/ National Highway Traffic Safety Administration (49 CFR PART 572) Anthropomorphic Test Devices, Subpart B.

/3/ Zellmer et al., Easy Test Assembly for Retractor Model Correlation; to be published

/4/ Voigt et al., to be published