A PROCESS TO QUALIFY A DUMMY MODEL FOR THE USE IN A VIRTUAL TESTING APPLICATION

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ABSTRACT

Finite element models of crash test dummies are extensively used throughout the development process of new cars. Each model has to go through various validation steps to meet user- or manufacturer-defined quality requirements. However, there is no standardized process established to qualify a model for a specific virtual testing application in general.

A consumer rating organization intends to include virtual testing in their rating protocol. The pilot use case will be a far side impact using the WorldSID 50th. Virtual testing requires validated models of environment, restraint systems, and dummy but there is no standard available to determine the level of validation.

This paper presents the work of an ACEA working group that developed a process to qualify WorldSID 50th dummy models for the use in a far side virtual testing application.

The validation processes including validation data of different WorldSID 50th models were reviewed. A multi-level procedure covers general properties, fundamental dynamic behaviour and application specific loadings. The assessment is based on pass/fail criteria as well as on objective rating methods. For final confirmation of the methodology four state of the art models and an artificially degraded model were used.

The designed process comprises three levels that need to be passed. It is only valid for applications that have very similar load levels and load patterns (reference application).

The first level checks general properties of the model against the hardware. It includes drawing conformity, external dimensions, range of motion of joints and mass properties. The second level checks the fundamental dynamic behaviour of the model. The model must pass all qualification requirements. The third level is derived from the reference application. It checks the performance of the most important components (body segments) and of the whole dummy. The boundary conditions of these checks are derived from the reference application. The relevant dummy signals are assessed by using the objective rating method defined in ISO/TS 18571 [1]. All signal scores are weighted and combined to a total rating. The assessed responses cover kinematics as well as internal loads. The model must achieve a minimum total rating score to pass this third level. A model is validated or qualified for the virtual testing application if all three levels are passed successfully.

The far side application requires a dynamic assessment of lumbar spine and neck. An additional sled test with a simplified vehicle environment evaluates the performance of the whole dummy model.

The process offers the opportunity to assess the level of validation based on objective criteria. It can distinguish between different levels of validation.

The process provides a method to qualify models for use in virtual testing based on objective parameters and rating schemes. It might become a standardized method to qualify the WorldSID 50th model as one component to introduce virtual testing.

INTRODUCTION

The intention of a consumer rating organization is to improve the crashworthiness of cars and thus the safety of the occupants. Therefore, they constantly track accident statistics and respond to clustered occupant injuries with tightened requirements or new tests. New approaches need to be considered because of limited testing resources. One of them is virtual testing. Such a use case requires well-validated models of all involved components. It includes the environment, the restraint system as well as the dummy.

Today's finite element (FE) models of crash test dummies are highly sophisticated. They are used to predict occupant loading and kinematics in various crash scenarios and the findings heavily influence the development process of new cars. They have to go through several validation steps, from single parts over whole components up to the dummy, to meet a quality which is defined by the manufacturer and the user. The level of validation depends on the criteria set and currently, there is no standard available to determine it. Furthermore, with regard to a specific virtual testing application, there is no standardized process established to qualify a dummy model.

This paper presents the work of an ACEA working group that developed a process to qualify various WorldSID 50th models for the use in a far side impact as a pilot use case for virtual testing.

QUALIFICATION PROCEDURE

The procedure to qualify an FE model for a specific virtual testing application is divided into various levels (see Figure 1). In each level a different aspect of the model is checked against the hardware dummy or the performance of the hardware dummy. They include the following in sequential order: general dummy properties, fundamental dynamic behaviour and the application-specific loading. Each requirement layer is evaluated with a criterion. If a criterion is fulfilled, the process continues with the next requirement level and after meeting all requirements, the model is considered qualified for the virtual testing application.

General model properties

The individual components of the FE model must match the drawings of the hardware within the accuracy of an FE modelling to ensure drawing conformity. The external dimensions of the model (e.g. whole body dimensions,

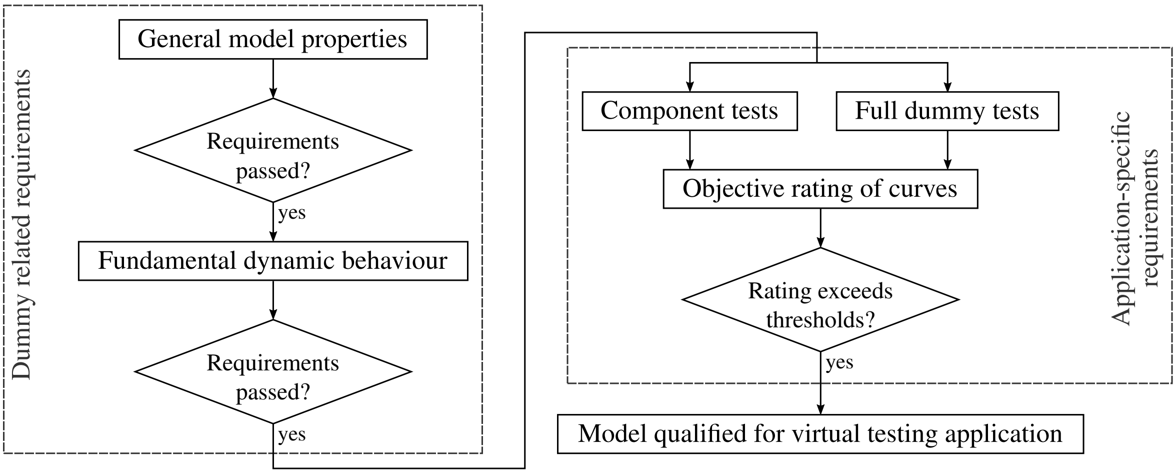

Figure 1. Overview of the qualification procedure with the different levels grouped into their dependency to dummy or application.

segment lengths) must also comply with the specifications of the hardware. Each joint has to be restricted in its range of motion according to hardware specifications. Also, the models mass properties of the body segments shall match the mass properties of the hardware dummy. These properties include overall mass, mass distribution and location of centre of gravity.

The requirements of the general model properties are evaluated with a pass/fail criterion.

Fundamental dynamic behaviour

The FE model must fulfil all the requirements of the certification/qualification/hardware validation test procedures of the hardware dummy, meaning that simulations of all qualification test must be conducted with the model.

The requirements regarding the fundamental dynamic behaviour have a pass/fail criterion.

Application-specific validity

This level includes two parts. In the first part the models validity based on the performance on component level is reviewed while in the second part the performance on full dummy level is evaluated. The simulations in both parts are based on tests which must have a loading level or load paths similar to the virtual testing application. The component level tests as well as the full dummy level tests must be designed with the virtual testing application in mind. Repeatability and reproducibility is a serious issue and shall be considered when creating data for the assessment of an FE model. It is recommended to run a sufficient number of tests with several specimen to get reliable data. The mean signals are used as reference to assess the FE model. Load case relevant signals of the tests should be selected and used for the rating.

The results of the simulations must be compared to the results of the hardware tests via the objective rating procedure described in the following sections. The rating method requires the definition of an evaluation interval. It must focus on the time frame in which the component or dummy moves with relevance to the virtual testing application, usually the loading phase. It may not start or end at the first or last data point of the simulation due to preprocessing. If necessary, a lead time or decay time must be taken into account in the simulations. A minimum value for the final rating score of both parts of the application-specific level must be defined.

Objective rating

The procedure to calculate final scores for the model performance on component and full dummy level is based on the comparison of the simulation data to the test data. It is divided into several steps. Prior to any calculation of a score, all signals must be preprocessed. Next, each signal of the simulation is rated with a signal score by applying the objective rating method in the evaluation interval. Subsequently, the signal scores are weighted and rating scores for all sensors are calculated, which in turn are used to calculate a final load case score.

Preprocessing of signal data All signals of the hardware tests and simulations must have the same sampling rate and must be filtered with CFC60 according to SAE J211 [2] or ISO 6487 [3]. A reference data set for each test configuration must then be created by calculating mean signals from the signals of the test repetitions. The time offset between comparison and reference data should be adjusted via a reference signal, e.g. the sled pulse.

Objective signal score Each signal is rated in the evaluation interval with a score, which is calculated using the objective rating metric described in the ISO/TS 18571 [1]. This method compares two time-history signals, the reference signal (test data) and the comparison signal (simulation data), by combining four different metrics to compensate disadvantages of the individual sub-metric (see Figure 2).

The corridor metric defines a narrow inner and a wider outer corridor around the reference signal. Those corridors are the green (inner) and yellowish (outer) areas around the blue reference signal in the first diagram in Figure 2. All time steps of the comparison signal (red) whose values are within the inner corridor are rated with the maximum score, i.e. 1. The opposite would be all time steps with values outside of the outer corridor. Those are rated with a minimum score, i.e. 0. The remaining time steps with values between the outer corridor and inner corridor are rated depending on the distance to the inner corridor. In this case, the score transitions from maximum to minimum with increasing distance to the inner corridor. The final score for the corridor metric is the average of all single time step scores.

The phase metric is used to evaluate the phase shift between the reference and comparison signal. This shift or phase lag is determined by calculating the cross-correlation value of the two time-history curves while shifting them against each other. With an increasing phase lag, the score decreases.

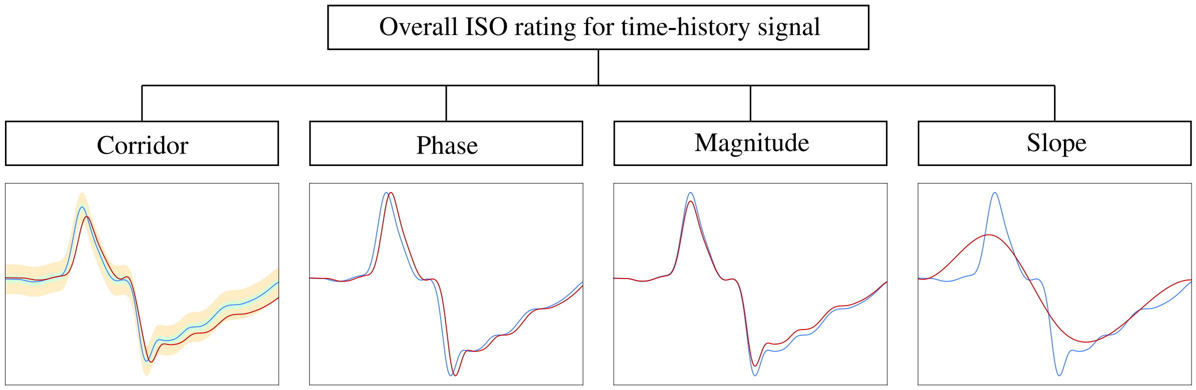

Figure 2. Composition of the overall score from the scores of different sub-metrics by means of the ISO/TS 18571 [1]. The diagrams show an example for each sub-metric with the reference (blue) and the comparison signal (red).

The difference in the amplitude between both signals is measured via the magnitude metric. Here, the information about the phase lag in combination with dynamic time warping (DTW) are used to reduce the influence of the phase and slope error between the two signals. The smaller the differences in the amplitudes after applying the phase shift and the DTW algorithm, the higher the magnitude score.

The score for the slope is a measure for the differences in slope of the reference and comparison signal. Therefore, both signals and in consideration of the phase lag are divided into small intervals in which the average slope is calculated. The resulting ”slope curves” are used to calculate the slope error by evaluating their difference.

Finally, all final scores of the four sub-metrics are weighted and combined into the overall score S_{Signal} of a single signal. The scores of the phase, magnitude and slope have the same weight whereas the corridor score has a doubled weight.

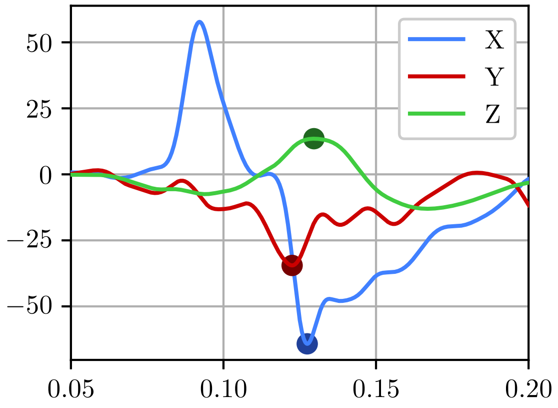

Figure 3. Reference sensor with three signals and highlighted absolute maxima.

Sensor score If a sensor consists of only one signal, the signal score is at the same time the sensor score S_{Sensor}. In case of multiple signals per sensor each signal score has to be weighted to calculate the sensor score S_{Sensor}.

The weighting w of a signal is determined from the reference data of each sensor. Therefore, the absolute maximum A of each reference signal per sensor has to be extracted. Figure 3 shows reference data of a tri-axial sensor with the absolute maximum of each signal highlighted. The weighting w of a signal is calculated according to Equation 1.

$$w_i = \frac{A_i}{\sum\limits_{j=1}^{n} A_j} \qquad i, j \in \mathbb{N} \qquad \textbf{Equation (1)}$$

The indices i and j are consecutive numbers for the signals and the index n is the number of signals of the sensor.

Equation 2 shows how the sensor score S_{Sensor} is calculated using all associated signal scores S_i and weightings w_i.

$$S_{Sensor} = \sum_{i=1}^{n} (w_i * S_i) \quad i \in \mathbb{N}$$ **Equation (2)**

The meaning of the indices is as before.

Load case score The load case score is calculated as the arithmetic mean of all sensor scores S_{Sensor} per load case (see Equation 3).

$$S_{Load\,case} = \frac{\sum_{i=1}^{n} S_{Sensor,i}}{n}$$ **Equation (3)**

In this case n is the number of sensors per load case, whereas the index i is a consecutive number for the sensors.

Overall scores for component and full dummy level The overall scores for component level as well as full dummy level test are calculated as the arithmetic mean of the according load case scores as shown in Equation 4.

$$S_{Component/Full\,dummy} = \frac{\sum_{i=1}^{n} S_{Load\,case,i}}{n}$$ **Equation (4)**

The meaning of the indices is analogously to the above.

EXAMPLE LOAD CASE

The described procedure was tested with an example load case: the WorldSID 50th in a far side application. For this purpose, the process was validated and verified by using four WorldSID 50th FE models that are used by the industry in their standard development processes. Additionally, an artificially degraded version of one of the models was also tested to ensure that the process is able to identify poor FE models. This degenerated model fulfils the first level of the process. The material properties of some parts were manipulated to worsen the dynamic behaviour.

General properties and dynamic requirements

The WorldSID 50th FE models must conform with the drawings of the dummy and must fulfil all specifications of the ISO 15830 [4]. These documents include external dimensions, range of motions of joints and mass properties.

The validation test procedures are also described in the ISO 15830. All FE models must pass the requirements of the various component and full body tests.

Application-specific validity

The application-specific validity of the WorldSID 50th FE models is assessed in two component tests and a full dummy sled setup.

The component tests include two variants of a mini-sled setup each for the head-neck and the lumbar spine. They differ in the direction of loading, pure lateral and oblique, for a sled pulse with a maximum acceleration of 35 g. The head-neck test setup contains the whole WorldSID 50th head-neck assembly down to the lower neck bracket which is mounted on the mini-sled via a swivel plate and an adapter socket. The head angular rates, the upper and lower neck forces and moments are measured and evaluated. The second component test setup includes the WorldSID 50th lumbar spine and the according lumbar load cell. The dummy thorax is represented by a mass replacement which is mounted on top of the lumbar spine. The entire assembly is mounted on the mini-sled via a swivel plate and an adapter. The measured and evaluated signals of the lumbar configuration include the angular rates of the mass replacement as well as the lumbar forces and moments. The duration of the evaluation interval for the assessment of the signal scores is 50 ms and 95 ms for the head-neck test and the lumbar spine test, respectively. It starts with the rising slope of the sled pulse. A score of 0.7 has to be exceeded in the overall component rating (Equation 5). The component test setups are shown in Figure 4.

$$S_{Component} \geq 0.7$$ **Equation (5)**

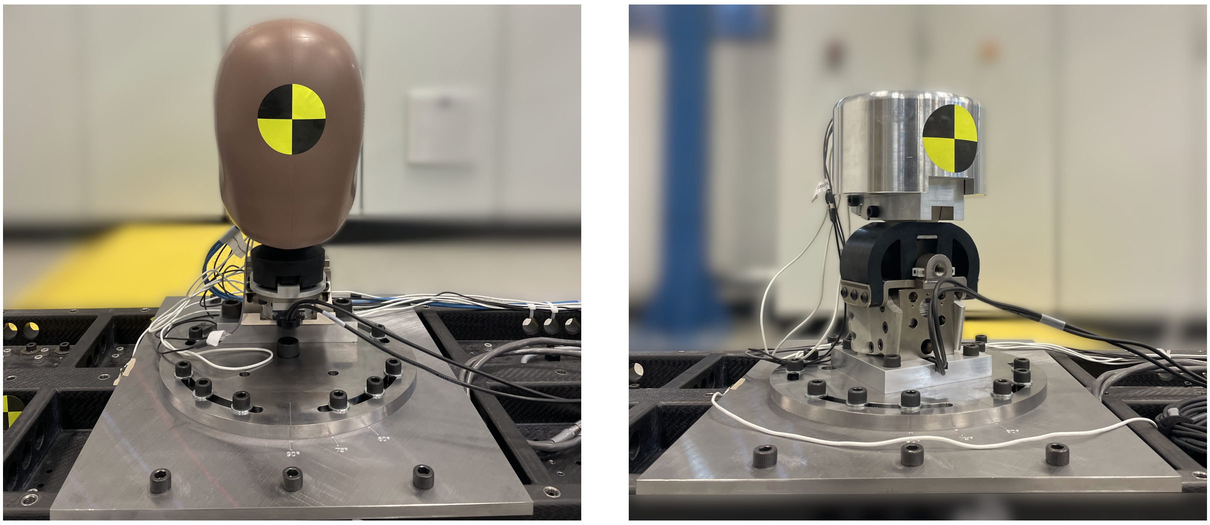

Figure 4. Head-neck lateral (left) and lumbar spine oblique (right) mini-sled test setups for component tests.

Figure 5. The image sequence shows a full dummy sled test.

The design of the full dummy sled setup is very close to the virtual testing application. A WorldSID 50th dummy is seated in a simplified vehicle environment. The surrounding structure features a rigid seat, a rigid foot rest and a centre console covered with a foam. The restraint system used includes a belt with a pretensioner. The entire sled setup is used in two tests - with a Δv of 8 m/s and 11 m/s. All evaluated signals are listed in Table 1. The interval of evaluation for the sled tests ranges from 0 ms to 140 ms (test with $\Delta v = 8$ m/s) and from 0 ms to 120 ms (test with $\Delta v = 11$ m/s). The minimum overall score for the sled tests is set to 0.6 (Equation 6). An image sequence of a sled test is shown in Figure 5.

$$S_{Full\,dummy} \geq 0.6$$ **Equation (6)**

Results

All FE models, including the artificially degraded one, were conform to the drawings and fulfilled the specifications of the ISO 15830 external dimensions, range of motions of joints and mass properties. The regular FE models also passed all requirements of the qualification tests. The modified model, however, failed the abdomen qualification test by approximately 3 % (approx. 1 mm).

Evaluation of the four models by the procedure yielded ranges of component load case scores of 0.690 - 0.823 (lumbar spine lateral), 0.717 - 0.875 (lumbar spine oblique), 0.678 - 0.762 (head-neck lateral), and 0.633 - 0.754 (head-neck oblique). The overall scores for component level were within a range of 0.712 to 0.786 for the state of

Table 1.
List of relevant outputs of the sled tests.

Angular rates	Head	**Displacements**	Second abdominal rib
Accelerations	Head	**Forces**	Upper neck
	Thorax T1		Lumbar spine
	Thorax T12	**Moments**	Upper neck
	Pelvis		Lumbar spine

the art models. The scores of the artificially degraded model in the component load case were 0.469 (lumbar spine lateral), 0.484 (lumbar spine oblique), 0.494 (head-neck lateral) and 0.519 (head-neck oblique), respectively. This resulted in an overall score of 0.492 on component level.

The load case scores for the sled configurations with the four models were in ranges of 0.629 - 0.717 (8 m/s) and 0.638 - 0.740 (11 m/s). The according overall scores were between 0.634 and 0.714. The degraded model scored 0.589 (8 m/s) and 0.606 (11 m/s) in the load cases and 0.597 in the overall sled score.

DISCUSSION

The procedure is a multi-level process to assess the model globally and based on the requirements of the reference application. The requirements of the first step, the general properties of the dummy, are used to check whether the model corresponds to the hardware in a static position. Here, drawing conformity ensures that the model correctly represents the individual parts. The proper assembly of the dummy model is tested by measuring and comparing the external dimensions and matching of mass properties with hardware data leads to the dummy specific mass distribution. Lastly, the defined range of motion restricts the joint configuration of the model. These general properties determine form and basic functional requirements of the FE model.

For a correct fundamental dynamic behaviour of the model the qualification tests must be passed. Realistic material properties and contact definitions are needed to meet the specified requirements. Up to this point, the model fulfilled the same requirements like the hardware dummy. Qualification tests do cover only a limited range of loading conditions and check only a limited number of dummy responses. In addition, only significant parts of the responses are restricted (e.g. peaks). This is not sufficient to assess the validity of an FE model. Furthermore, the load levels in the qualification tests do not necessarily correspond to the levels in real testing and the load paths in real testing are possibly not covered with these tests, too. Hence, more advanced tests are needed to eliminate these shortcomings in model validation for virtual testing applications.

For this reason, the application-specific validity of the model is thoroughly assessed in additional performance tests, the component tests and the advanced full dummy tests. With the latter test type the overall model performance shall be evaluated. Here, the dummy kinematics as well as the internal loads are considered in an environment very similar to the final application. However, a model can be tuned to perform particularly well in a sled environment, which is why the component tests are performed. They provide a deeper look into the load case relevant parts of the model. The loading levels and load paths are similar to the ones in vehicle tests. Hence, they are very important to check the validity of the model with regard to the virtual testing application. Furthermore, they are used to validate non-standard signals. The main focus of the component tests is to identify FE models with flaws or ones that have been tuned for a specific test or situation.

In the evaluation of the performance tests, the previously neglected signal characteristic is relevant. Due to the subjectivity of manual evaluation of the signal characteristic, an objective rating method (ISO/TS 18571) is used in the loading phase of the test. This restriction of the evaluation window is necessary because only the relevant loading period should be rated with a score. By extending this time frame, a starting phase without load would improve the score without the model actually working better, or the hard-to-predict unloading phase would unnecessarily reduce the score. The interval should not start with the first or end with the last data point of a signal because this could introduce errors when filtering the signal for the rating method. Usually, this has to be considered in the simulations, where an additional lead time would be necessary.

As a preparation for the objective rating method the filtering of all signals is unavoidable, because the algorithm cannot evaluate strong oscillation. Furthermore, the metric is not able to handle reference signals of multiple tests. Hence, a mean reference data set had to be created from the test repetitions of each configuration. It is also not possible to compare more than two signals. This is the reason why only a signal score was calculated by means of the ISO/TS 18571.

Usually, a sensor consists of more than a single signal and the significance of each signal is dependent on the actual load case. With regard to an objective influence of the respective sensor shares, the described method with individual weights of the signals was used for the sensor score. This method included all signals in the calculation of the scores with a weight based on the amplitude of the reference signal. This way minor axes of a sensor had a reduced effect on the score but were not neglected. Furthermore, it was not necessary to subjectively pre-select specific signals and possibly neglect problems in unconsidered ones. However, the reference signals had to be free of signal spikes and the like.

The application-specific or performance tests were designed based on the review of the validation process including validation data of different WorldSID 50^{th} models. The head-neck component and the lumbar spine were identified as the most important dummy parts regarding the virtual testing application. Therefore, they were tested with a load level derived from the reference application and in two directions to cover a wider range of loading paths. The full dummy sled test was used because it evaluates the overall FE model performance in an environment very similar to the virtual testing application. The signals to be evaluated were selected based on their importance for the load case and on the experience gained from the validation processes. The artificially degraded model was used to ensure that the process is able to identify ”poor” models.

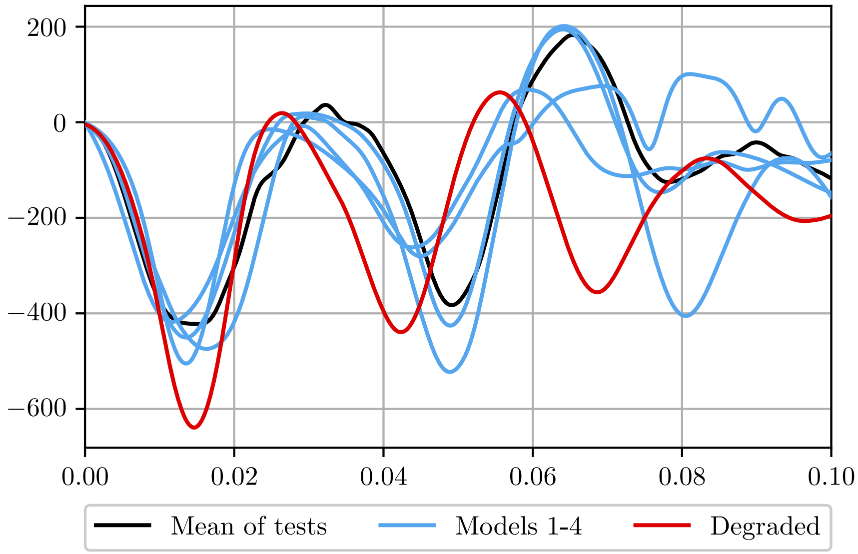

Figure 6. Comparison of the results of one signal in lumbar spine oblique configuration.

The resulting scores for the four state of art models exceeded the defined limits of the overall score. The manifold experiences and the long-term use of those models certainly contributed to these scores. The gap of 0.037 between the overall score of the sled test of the regular models and the degraded model is small. However, the difference in the overall score for the component tests between these models (above 0.712 compared to 0.492) is significant. Figure 6 shows an example signal of the lumbar spine oblique configuration, where the deviation of the degraded model is clearly visible. It differs much more in the amplitude and phase from the reference than the other models. All this is proof that a model can be tuned to pass the requirements of a specific application but fails when looking at details (component level). It must be noted, however, that the basis for the artificially downgraded model is one of the state of the art models and that the downgrade includes only a few materials.

LIMITATIONS

The process was only validated by using one dummy type in a single application. A general validity must be checked with other dummy types in other applications. Furthermore, the outcome of the process is dependent on the selection of the requirements. Neglecting relevant dummy components and signals or low limits of the scores can reduce the validity of the evaluation. This could lead to unsuitable models successfully passing the requirements.

CONCLUSIONS

The developed process provides a method to qualify FE models for use in virtual testing based on objective parameters and rating schemes. In the example case, the four assessed state of the art models successfully passed all requirements. Furthermore, they showed a clear gap in the score to the artificially degraded model. Therefore, the process could be a standardized method to qualify the WorldSID 50^{th} model as one component to introduce virtual testing in a far side application.

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