UNIVERSITÀ DEGLI STUDI FIRENZE

UNIVERSITÀ DEGLI STUDI FIRENZE DICEA DIPARTIMENTO DI INGEGNERIA CIVILE E AMBIENTALE

Road safety through FEM simulations: concepts and criteria towards a 0-deaths strategy

Validation and verification process

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The FEM Methods

The Finite Element Method (FEM) is now regularly used by engineers to analyse the crashworthiness performance of roadside safety barriers.

Computer FEM simulations allow investigating the performance of new designs or retrofitted modifications to existing systems.

However, it is essential that the numerical model is accurately verified and validated to provide reliable results.

In particular, quantitative methods should be suggested to pursue an objective assessment of the analysis.

The FEM Methods

Validation and Verifcation (V&V)

The most used in USA

NCHRP 22-24

Pr UNI EN 1317-5

The most used in Europe

Not mandatory…but ..

The two methods are based on the same criteria…but differ in the methodology

V & V process

Need and objectives

Recently, the US Federal Highway Administration (FHWA) has proposed a procedure to formally accept improved versions of roadside safety hardware that require only minor changes with respect to previous successfully-tested designs for cases in which these analyses are purely based on numerical simulations (FHWA, 2012). Following is an overview of the steps involved in this proposed process:

- Develop a model of the roadside safety hardware that has already been tested and approved through dynamic testing. This is referred to as the *baseline* model;
- Validate the results of the computer simulation of the baseline model against the already-existing crash test(s);
- Modify the baseline model to replicate minor changes in the structure and perform the simulations of the new configuration;
- Evaluate the results of the new design configuration using the same requirements for the crash tests. If simulation results indicate acceptable performance according to the test guidelines for roadside hardware design, the new design configuration can be approved for use.

An objective assessment of the baseline model through a rigorous Verification and Validation (V&V) process is essential to guarantee that the entire proposed acceptance procedure can deliver reliable results.

V & V process

What mean verification and validation??

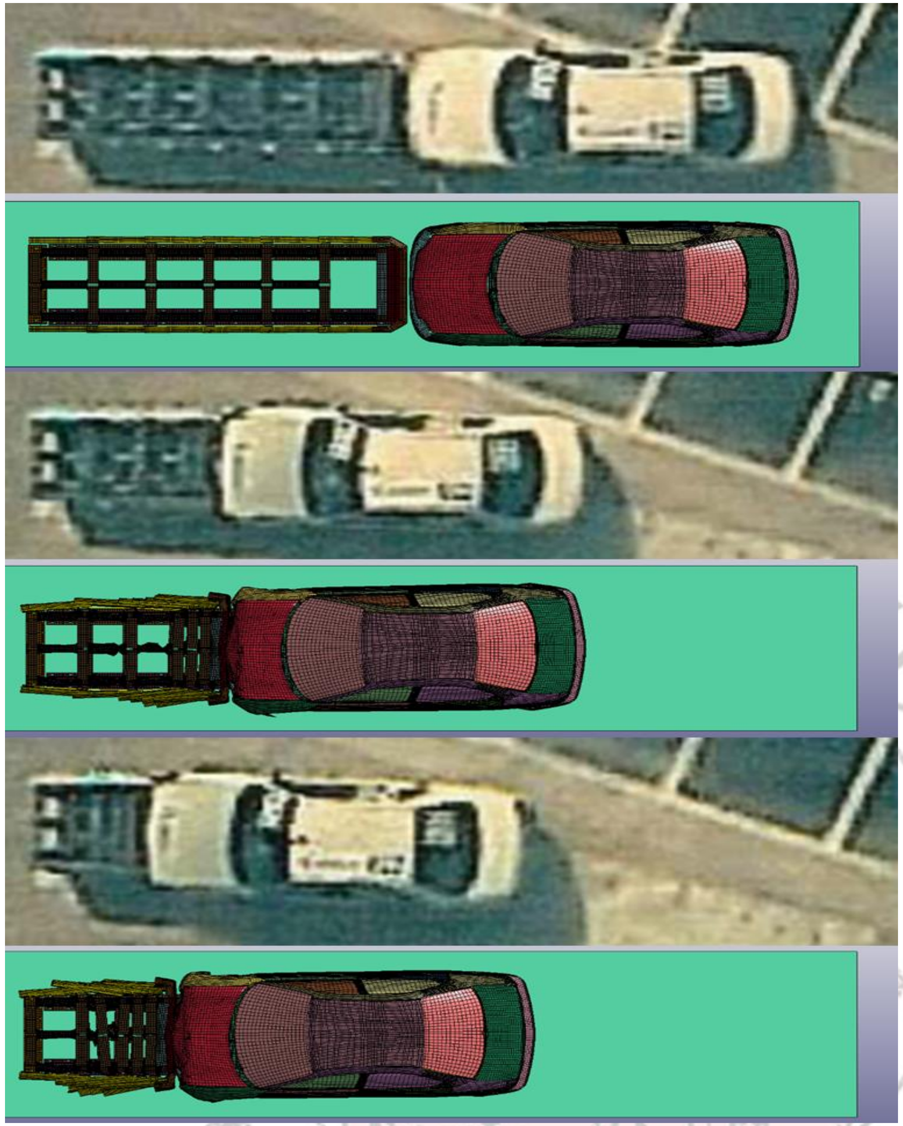
Definitions formulated by the American Society of Mechanical Engineers:

- **Verification** is defined as the process of determining that a computational model accurately represents the underlying mathematical model and its solution.

- **Validation** is defined as the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model.

V & V process

In practice, verification is the process of checking that the numerical model has been properly implemented, while validation ensures that the results obtained from the model are consistent with the real world. In particular, the question at the root of the validation exercise in roadside safety is whether the simulation replicates the physical experiment and, consequently, whether it can be used to explore and predict the response of new or modified roadside hardware in the real-world.



V & V process

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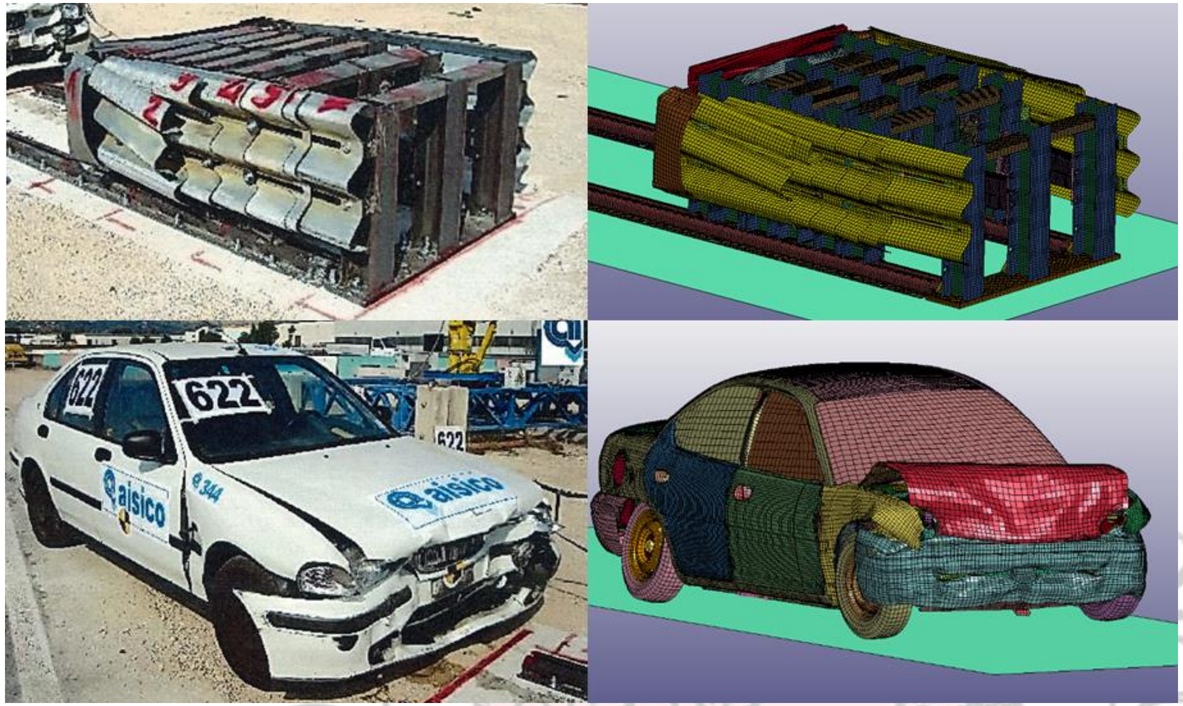

Comparison metrics

A variety of validation metrics can be found in literature but essentially they can be grouped into two main categories:

1. deterministic metrics → pr EN UNI 1317-5
2. stochastic metrics. → NCHRP 22-24

V & V process

Table 1. Comparison Metrics and Acceptance Criteria for V&V in Roadside Safety [1,2]

		Formulation	Acceptance Criteria
Sprague & Geers	Magnitude Component (M_{SG})	$M_{SG} = \sqrt{\frac{\sum c_i^2}{\sum m_i^2}} - 1$	$\boxed{\leq 40\%}$
	Phase Component (P_{SG})	$P_{SG} = \frac{1}{\pi} cos^{-1} \frac{\sum c_i \ m_i}{\sqrt{\sum c_i^2 \sum m_i^2}}$	$\boxed{\leq 40\%}$
ANOVA (based on residual error*)	Average ($\bar{e}^r$)	$\bar{e}^r = \frac{\sum_{i=1}^{n} (m_i - c_i)/m_{max}}{n}$	≤ 5%
	Standard Deviation (σ^r)	$\sigma^r = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (e^r - \bar{e}^r)^2}$	≤ 35%
	(*) normalized to the peak of the measured values		

(1) m_i and c_i are the values at the i^{th} sampled point of the measured and computed curves, respectively.
(2) Both the measured and computed curves are assumed to have the same constant sampling rate.

m: measured
c: computed

Both computed and measured data need to have the same sampling rate

percentile

V & V process

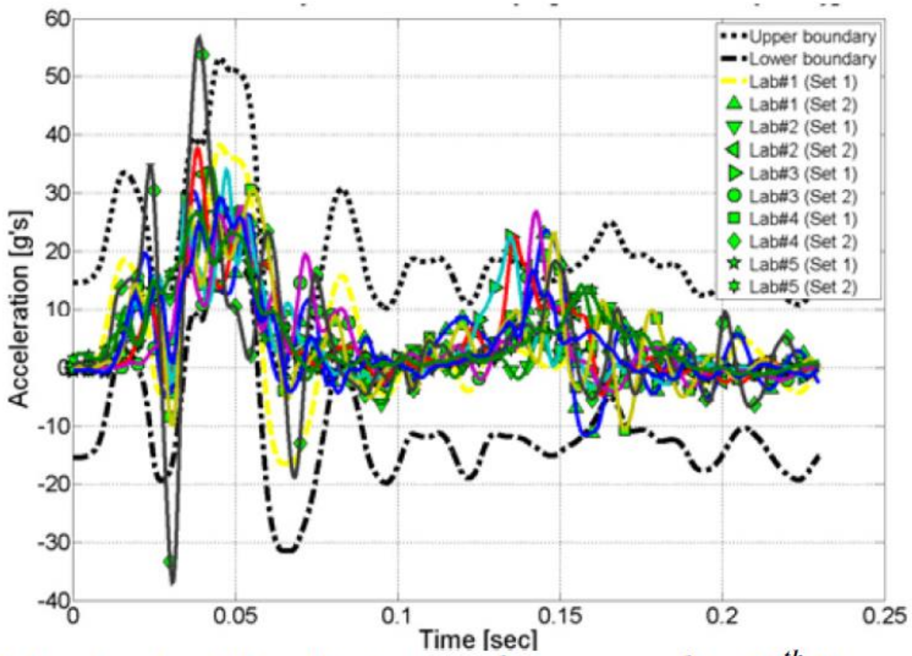

Figure 1. Lateral Acceleration Time Histories and Corresponding 90th Percentile Envelope for the Ten Repeated Full-Scale Crash Tests

An analysis of ten repeated full-scale crash tests was performed. The scatter in the metric values obtained from this analysis provided a good basis for determining reasonable acceptance criteria for these metrics. In fact, using this approach, it was possible to define the acceptance based on actual probabilistic variation of the experimental results.

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V & V process

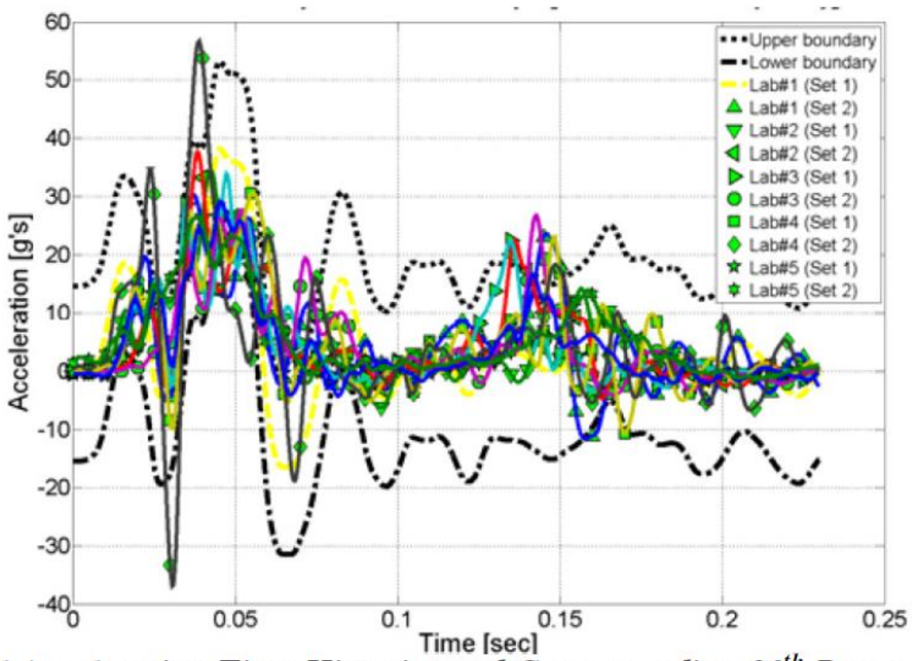
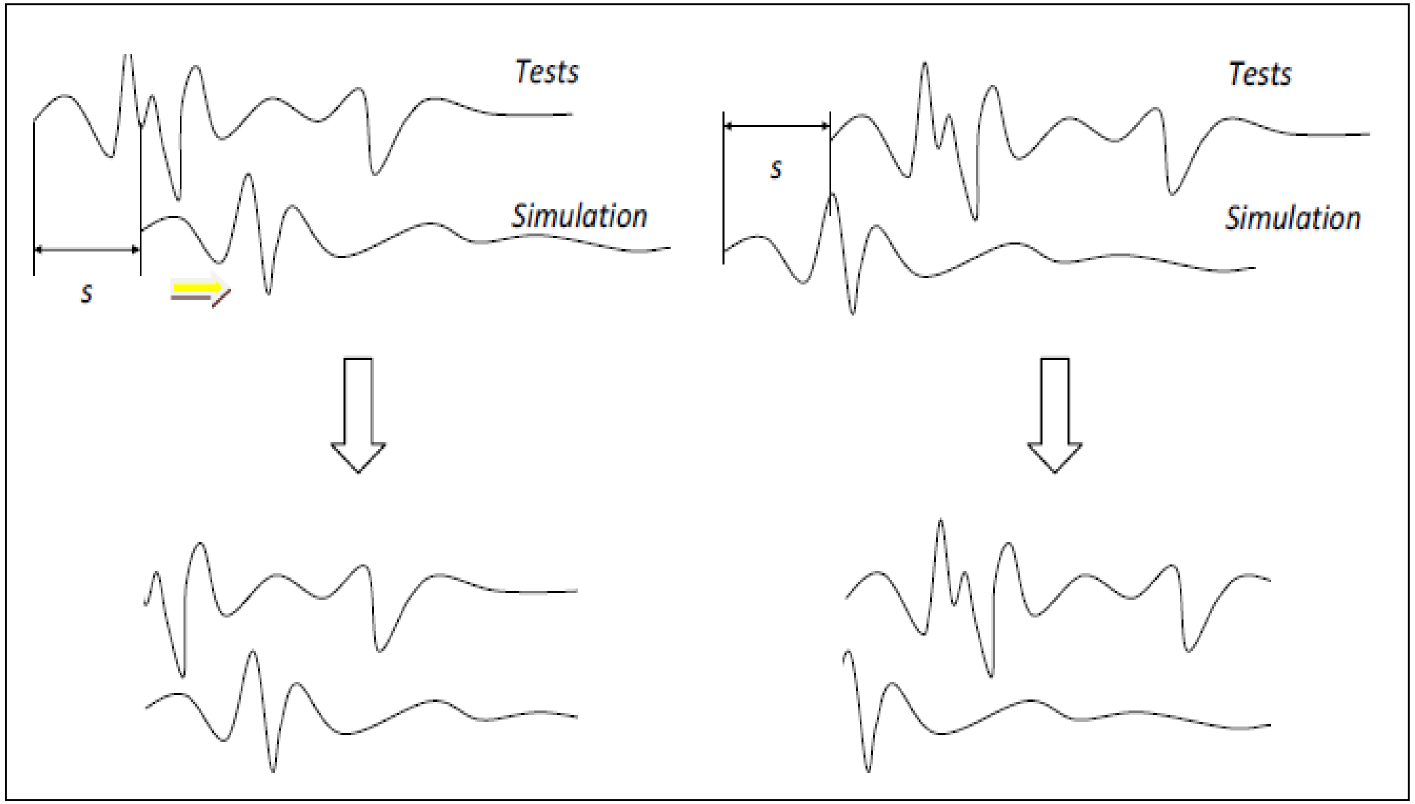


Figure 1. Lateral Acceleration Time Histories and Corresponding 90th Percentile Envelope for the Ten Repeated Full-Scale Crash Tests

All ten crash tests were performed on the same type of rigid concrete barrier.

For five of the tests, 2000 model Peugeot 106 test vehicles were used, while for the other five tests different vehicle makes and models were used. For all ten tests, the vehicles were compliant with the standard 900-kg small test vehicle specified in the European crash test standard EN 1317. The plot of the vehicle's lateral acceleration time histories that were used to determine the acceptance criteria, along with the corresponding 90th percentile corridor.

V & V process



The parameters compared must be of the same kind, ie they must have the same unit of measure, equal time of the measurements and equal length of the sample of the data in order to follow a correct, homogeneous and reliable procedure.

In order to make an easily comparison it is also necessary for the two curves to have the same characteristics: the same sampling interval and the same starting point.

V & V process

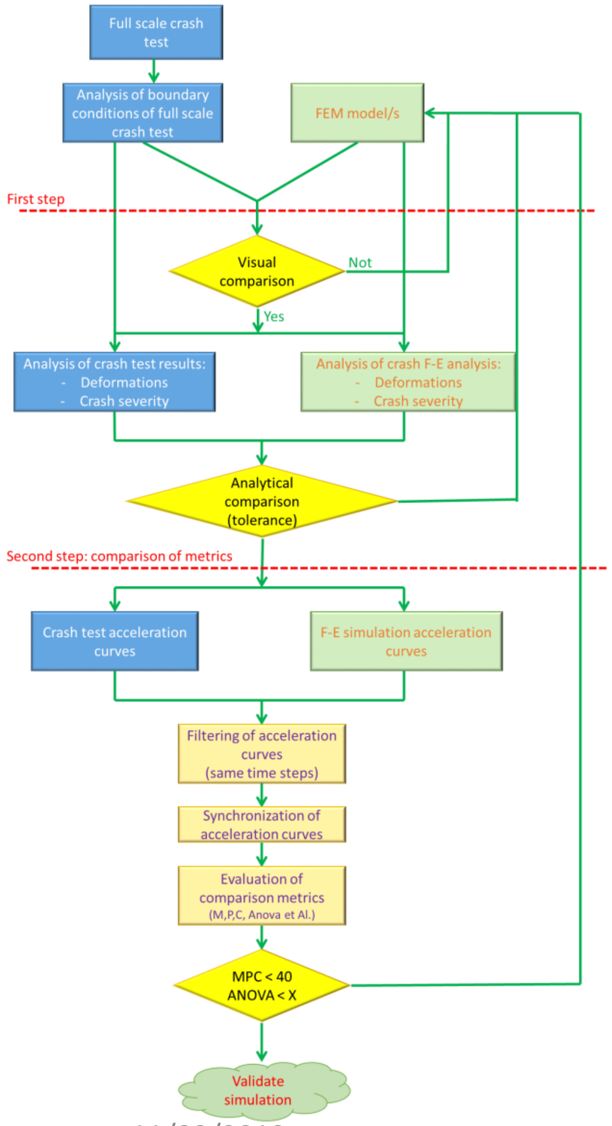
When a model has been validated for a particular application, it may not be appropriate for use in other situations that vary significantly from the intended original scenario.

non-repeatable procedure

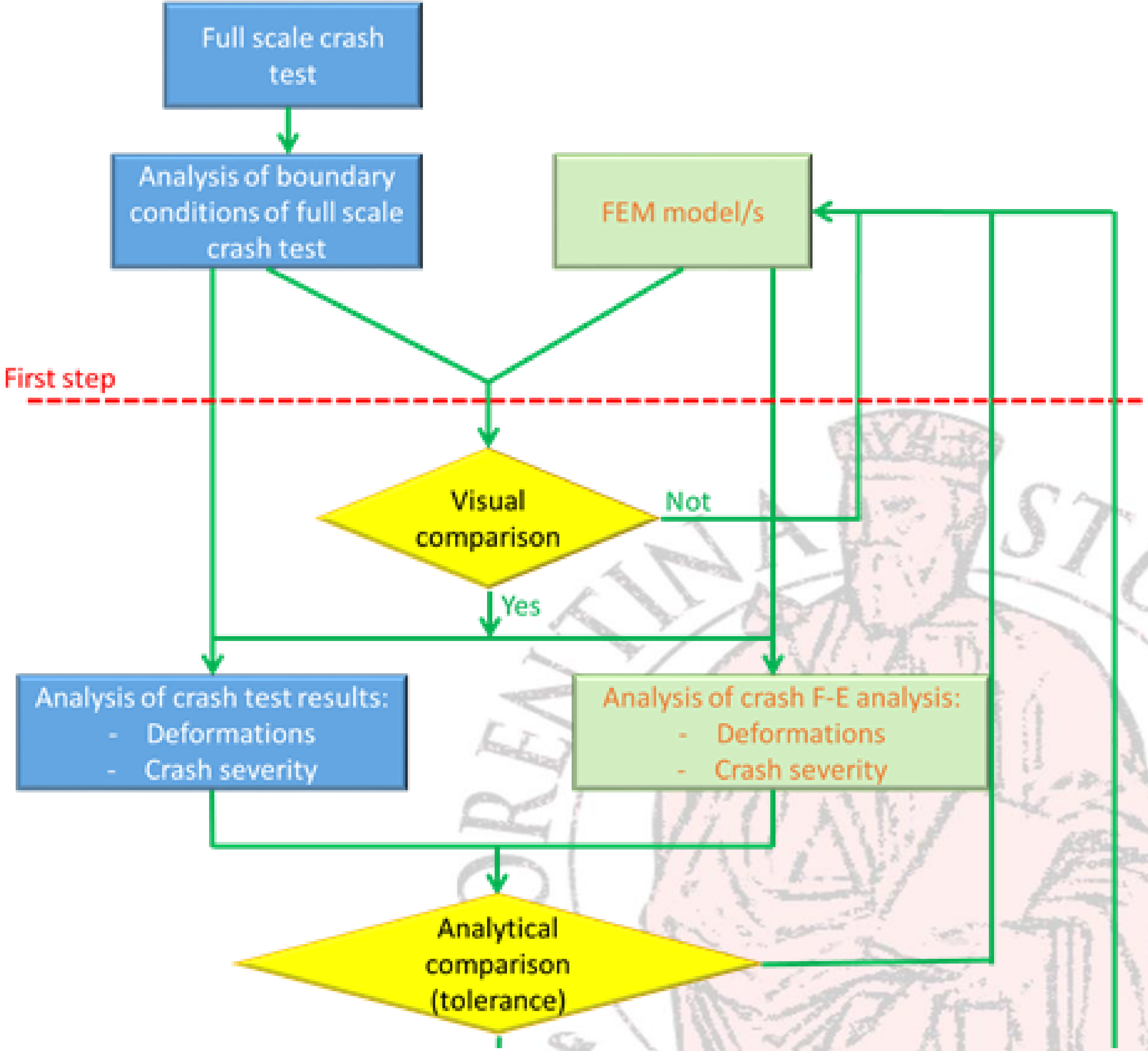
It is important that users other than the original developer(s) of a model fully understand whether the various components of the model accurately simulate the phenomena.

objective to the study of the original model

V & V process



Full scale crash test
Analysis of boundary conditions of full scale crash test
FEM model/s
First step
Visual comparison
Not
Yes
Analysis of crash test results:
- Deformations
- Crash severity
Analysis of crash F-E analysis:
- Deformations
- Crash severity
Analytical comparison (tolerance)
Second step: comparison of metrics
Crash test acceleration curves
F-E simulation acceleration curves
Filtering of acceleration curves (same time steps)
Synchronization of acceleration curves
Evaluation of comparison metrics (M,P,C, Anova et Al.)
MPC < 40
ANOVA < X
Validate simulation



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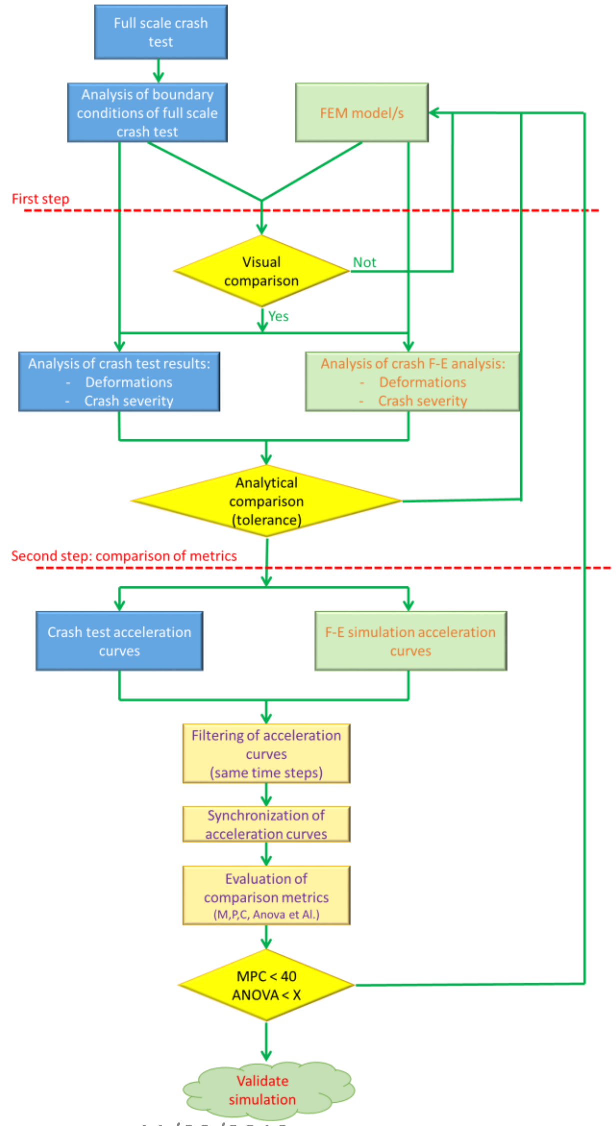
V & V process



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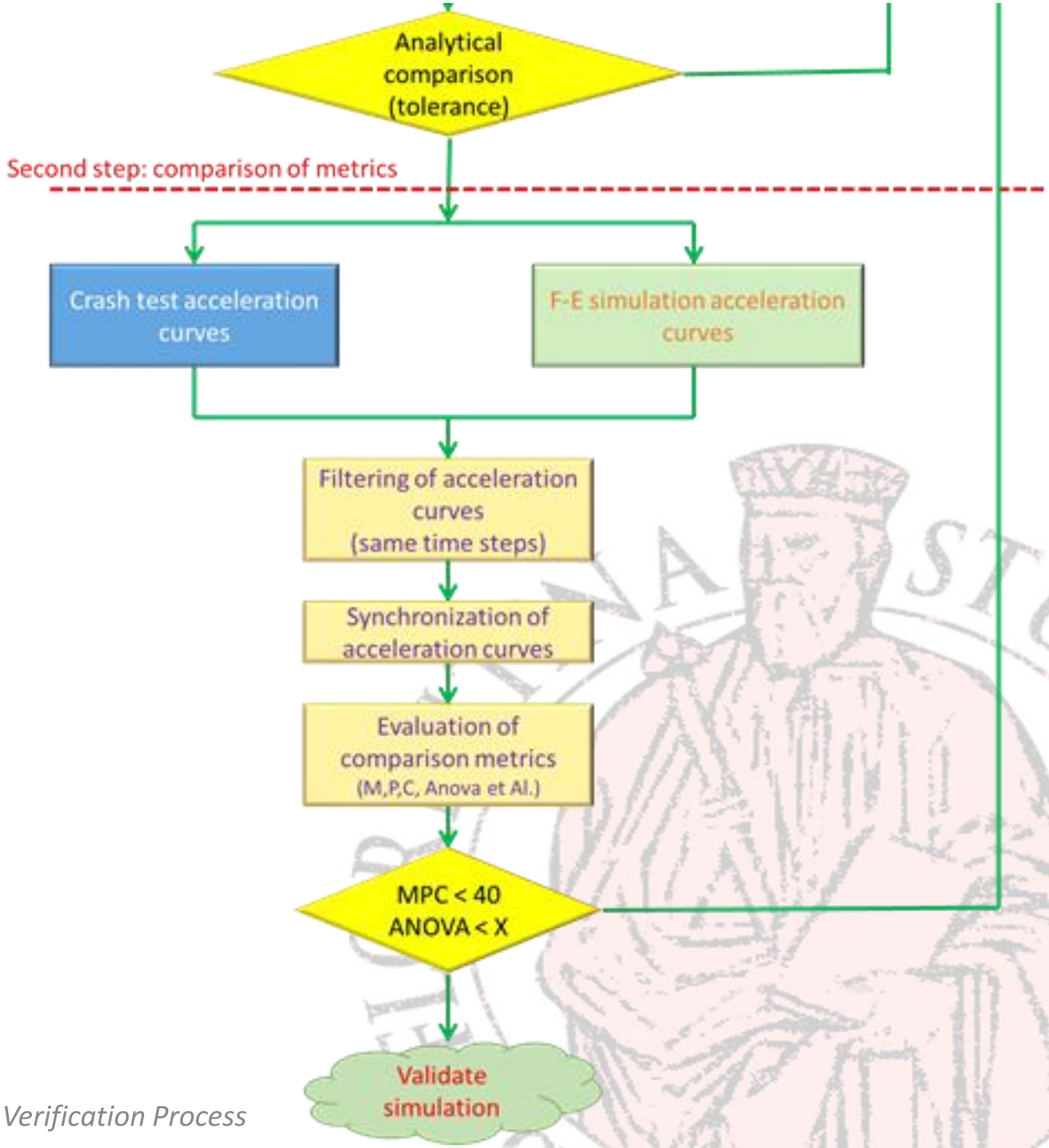

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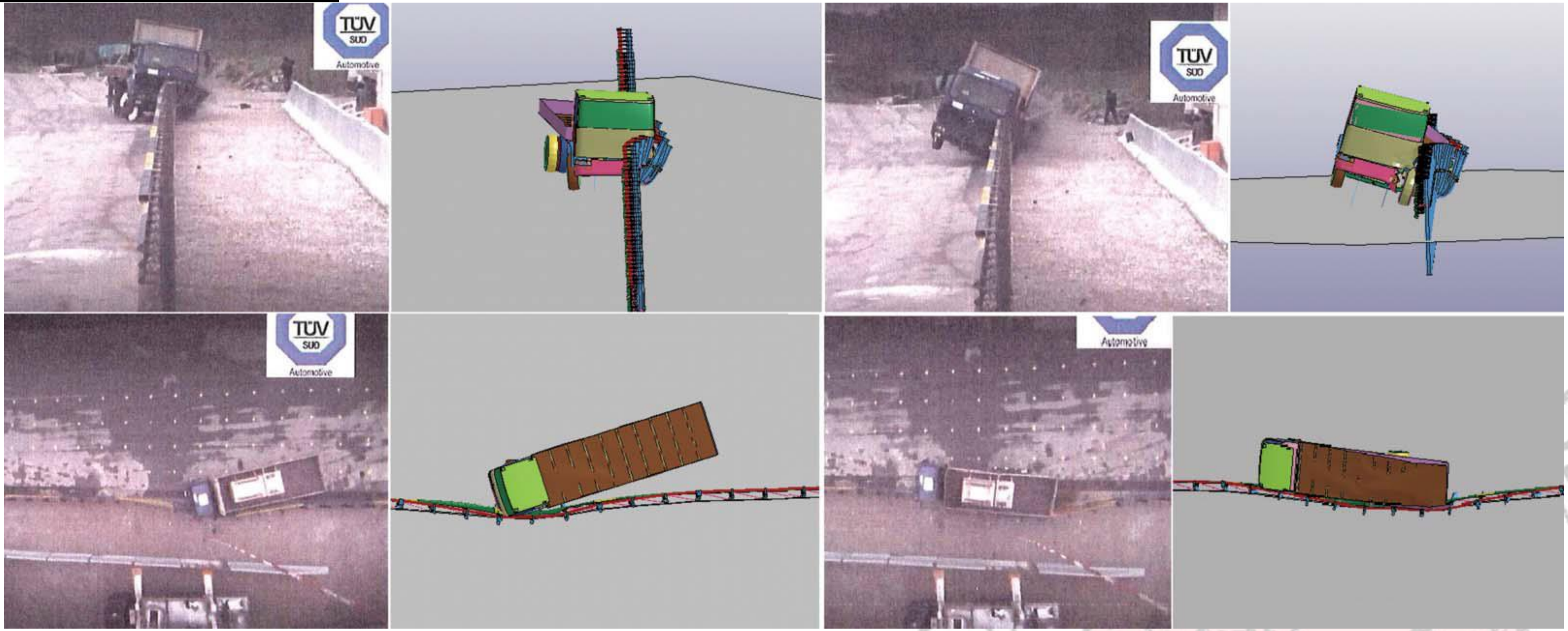
Validate simulation

For example

Visual comparison



In the first phase a visual comparison of the evolution of the two crashes (real and simulated) is conducted.

The visual analysis has shown a very good correlation between the real crash test and the simulated crash

For example

Consistence between real and FEM

Table 1. Comparison between the real and the FEM analysis values.

	Crash test		FEM analysis		
Parameters	m	s	m	s	Comparison V&V
Max working width (*W*)	2.00 m	N/A	1.81 m	0.57	+9.5% ok
Max dynamic deformation (*D*)	1.77 m	N/A	1.62 m	0.57	+9.2% ok
Max static deformation (Dst)	1.05 m	N/A	0.94 m	0.57	+11.7% fail
Impact energy	497 kJ		497 kJ		−0.14% ok

In the second phase the consistence of the static, dynamic and energy indices were performed.

Only the static deformation appears to be slightly higher than the real static deformation.

Metric comparison

The last part of the calibration process, derived from the NCHRP procedure, is based on the comparison between the acceleration curves measured in the crash tests and those calculated in the FE simulation.

$$M_{\mathrm{G}} = \sqrt{\frac{\sum c_i^2}{\sum m_i^2}} - 1. \qquad (1)$$

$$C = \sqrt{M_{\mathrm{SG}}^2 + P_{\mathrm{SG}}^2}. \qquad (3)$$

$$P_{\mathrm{SG}} = \frac{1}{\pi} \frac{1}{\cos\left(\frac{\sum c_i m_i}{\sqrt{\sum c_i^2 \sum m_i^2}}\right)}. \qquad (2)$$

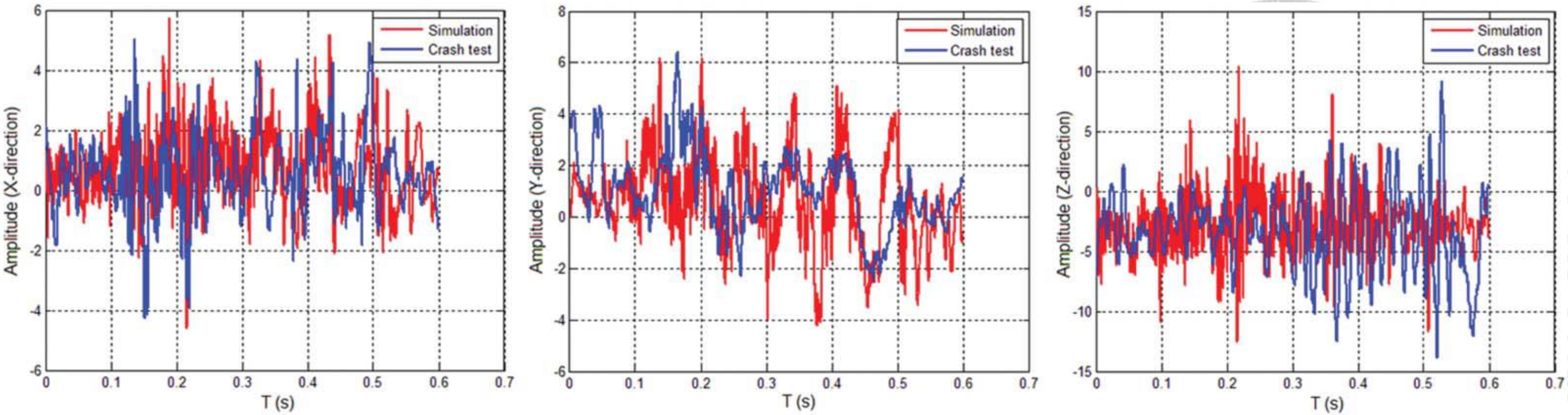
For example

Metric comparison

Table 2. Values of the M, P and C metrics for each direction.

	Values (%)		
Components	x	y	z
M_{SG}	2.6	2.0	−21.7
P_{SG}	39.7	37.1	30.2
C_{SG}	39.8	37.1	37.2
Check	Pass	Pass	Pass

The last part of the calibration process, derived fro[illegible]d on the comparison between the acceleration curves measured in the crash tests and those calculated in the FE simulation.



RSVPP tool

For example

Metric comparison

All the tests conducted show that the barrier model is accurate in reproducing the behaviour of the real system and this model is therefore used as a component in the full vehicle-safety barrier-sign model.

Table 2. Values of the M, P and C metrics for each direction.

	Values (%)		
Components	x	y	z
M_{SG}	2.6	2.0	−21.7
P_{SG}	39.7	37.1	30.2
C_{SG}	39.8	37.1	37.2
Check	Pass	Pass	Pass

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This European Standard specifies requirements, test methods and assessment methods, acceptance criteria and methods for verification of constancy of performance of the following vehicle restraint systems to be used as permanent on the roads and in vehicle circulation areas:

- safety barriers (including vehicle parapets),
- crash cushions,
- terminals,
- removable barrier sections,
- temporary barriers are regulated by National or local Authorities, however, their performance evaluation can be made according to this standard.

Pedestrian parapets and motorcyclist protection systems (non vehicle restraint function) requirements are not included in this European Standard.

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prEN 1317-5:2013 (E)

Not mandatory…but ..

Annex F
(normative)

Virtual Testing – Validation procedure

The purpose of this Annex is to define the validation and verification process for the use of virtual testing inside the current standard for simplified type testing, including procedures and acceptance criteria.

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1. Validation is based on the comparison between physical tests and virtual tests based on equal initial conditions (according to EN 1317-1:2010).
2. The reports for virtual testing <u>shall be assessed by an independent expert</u> chosen by the Certification Body.
3. The general validation criteria are described in G.4.3

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Table G.1 — Comparison table - Safety barriers

Critical behaviour	**Is VT in accordance with result from physical test?**
Containement	Yes/no
Rollover	Yes/no
Exit box (EN 1317-2:2010, subclause 4.3)	Yes/no
Wheel trajectory (EN 1317-2:2010, subclause 4.3)	Yes/no
Failure of longitudinal elements	Yes/no
Penetration of parts of VRS inside the vehicle	Yes/no
General criterion	**Is VT in accordance with the requirements**
Dynamic deflection criterion (G.4.2.3)	Yes/no
Working width criterion (G.4.2.4)	Yes/no
Vehicle intrusion criterion (G.4.2.5)	Yes/no

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Table G.2 — Comparison table - Crash cushion

Critical behaviour	Is VT in accordance with result from physical test?
Containment	Yes/no
Rollover	Yes/no
Redirection zone (EN 1317-3:2010, subclause 6.3)	Yes/no
Failure of longitudinal elements	Yes/no
Penetration of part of the crash cushion inside the vehicle	Yes/no
General criterion	**Is VT in accordance with the requirements**
Lateral displacements criterion (G.4.2.6)	Yes/no

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Table G.3 — Comparison table – Terminals

Critical behaviour	Is VT in accordance with result from physical test?
Containment	Yes/no
Rollover	Yes/no
Redirection zone (EN 1317-7:2010, subclause 5.6.3)	Yes/no
Failure of longitudinal elements	Yes/no
Penetraion of part of the terminal inside the vehicle	Yes/no
General criterion	**Is VT in accordance with the requirements**
Lateral displacements criterion (G.4.2.6)	Yes/no

Dynamic Deflection

The Dynamic Deflection (DD) from the physical test has to be compared with the one calculated from the virtual test (DDv)

The difference between the two dynamic deflections has to be less than the value calculated with the equation below:

$$|DD - DDv| \leq (0.1 + 0.2DD) \rightarrow \text{TB 11}$$
$$|DD - DDv| \leq (0.1 + 0.1DD) \rightarrow \text{other tests}$$

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Working Width

The Working Width (WW) from the physical test has to be compared with the one calculated from the virtual test (WWv)

The difference between the two working widths has to be less than the value calculated with the equation below:

$$|WW - WWv| \leq (0.1 + 0.2DD) \rightarrow \text{TB 11}$$
$$|WW - WWv| \leq (0.1 + 0.1DD) \rightarrow \text{other tests}$$

Vehicle Intrusion

The Vehicle Intrusion (VI) from the physical test has to be compared with the one calculated from the virtual test (VIv)

The difference between the two vehicle intrusions has to be less than the value calculated with the equation below:

$$|DD - DDv| \leq \boxed{(0.2 + 0.1DD)}$$

Lateral displacements for crush cushions and terminals

The lateral displacement LD for crash cushions and terminals for the physical test has to be compared with the one calculated from the virtual test LDv.

The difference between the two lateral displacements has to be less than the value calculated with the equation below:

$$|LD - LDv| \leq (0.1 + 0.2measure)$$

Additional controls

When the virtual test and the physical test are performed with a car additional parameter shall be compared to assess the quality of the virtual testing. Therefore, the validation process requires additional criteria.
"Yes" is to be ticked if there is agreement between the virtual testing and the physical test in accordance with the criteria defined.

Criteria	Is VT in accordance with result from physical test?
ASI criterion (G.4.2.9)	Yes/no
THIV criterion (G. 4.2.9)	Yes/no
Time histories criteria (G. 4.2.10)	Yes/no

Severity indices

EN 1317-1:2010 defines procedures to calculate severity indices values when a car (900 kg or 1500 kg) is used in a crash test for roadside hardware approval.

ASI

Table G.5 — ASI tolerance

	Tolerance	Time max ASI
ASI	± 0,1	± 0,05 s

Severity indices

EN 1317-1:2010 defines procedures to calculate severity indices values when a car (900 kg or 1500 kg) is used in a crash test for roadside hardware approval.

THIV

Table G.6 — THIV tolerance

	Tolerance	Time flight
THIV	± 3 km/h	± 0,05 s

Time hystories

The comparison is based on longitudinal and transversal components (related to the test article) of the vehicle’s velocity in the plane motion and on the yaw angle.

Time hystories

The virtual test is considered validated when the following requirements are matched:

- The numerical longitudinal and trasversal components of the velocity related to the test article remain inside a window built around the physical velocity components until the farthest in time amongst the max ASI time and the time of flight is reached. When the validation is requested for a modified product, the numerical velocity time history must <u>remain inside the window until the vehicles have loaded the modified components.</u>

The variation limits for the window are: ±4% of the initial resultant velocity and ±.01 s in time. For frontal centered tests for crash cushion and terminals the comparison will be based only on global resultant velocity.

Time hystories

The virtual test is considered validated when the following requirements are matched:

- The numerical yaw angle of the vehicle remains inside a window built around the physical yaw angle until the farthest in time amongst the max ASI time and the time of flight is reached. When the validation is requested for a modified product, the numerical velocity time history <u>must remain inside the window until the vehicles have loaded the modified components.</u>

The variation limits for the window are: ± 2.5% of the maximum yaw angle and ± 0,01 s in time.

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Verification

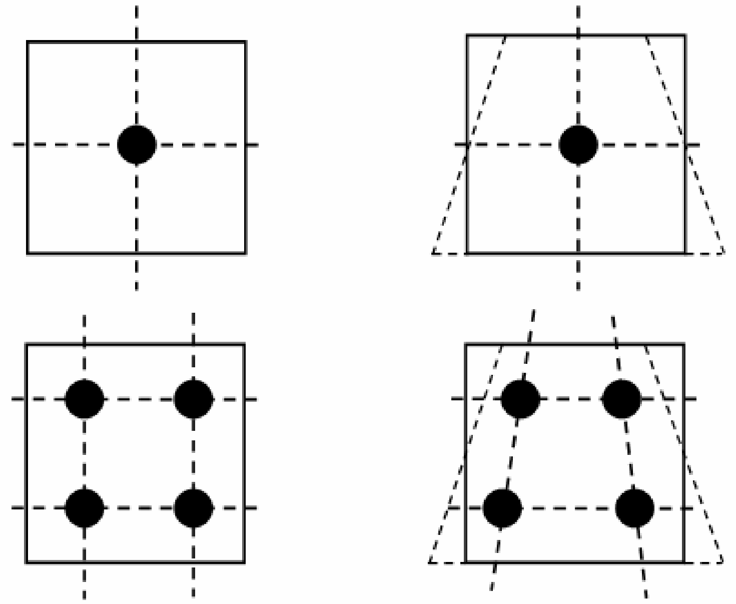
For both process

Table G.7 — Verification Evaluation Criteria for Finite Elements model

Verification Evaluation Criteria	Change (%)	Pass?
Total energy of the analysis solution (i.e., kinetic, potential, contact, etc.) must not vary more than 10% from the beginning		
Hourglass Energy of the analysis solution is less than 5% of the total initial energy at the beginning of the run.		
Hourglass Energy of the analysis solution at the end of the run is less than 10% of the total internal energy at the end of the run.		
At the end of the run The part/material with the highest amount of hourglass energy is less than 10% of the total internal energy of the part/material.		
Mass added to the total model is less than 5% of the total model mass at the beginning of the run.		
The part/material with the most mass added had less than 10% of its initial mass added.		
The moving parts/materials in the model have less than 5% of mass added to the initial moving mass of the model.		
There are no shooting nodes in the solution?		
There are no solid elements with negative volumes?		

The process does not exclude difference greater than those shown in the table as long as they are single and justified.

Hourglass energy



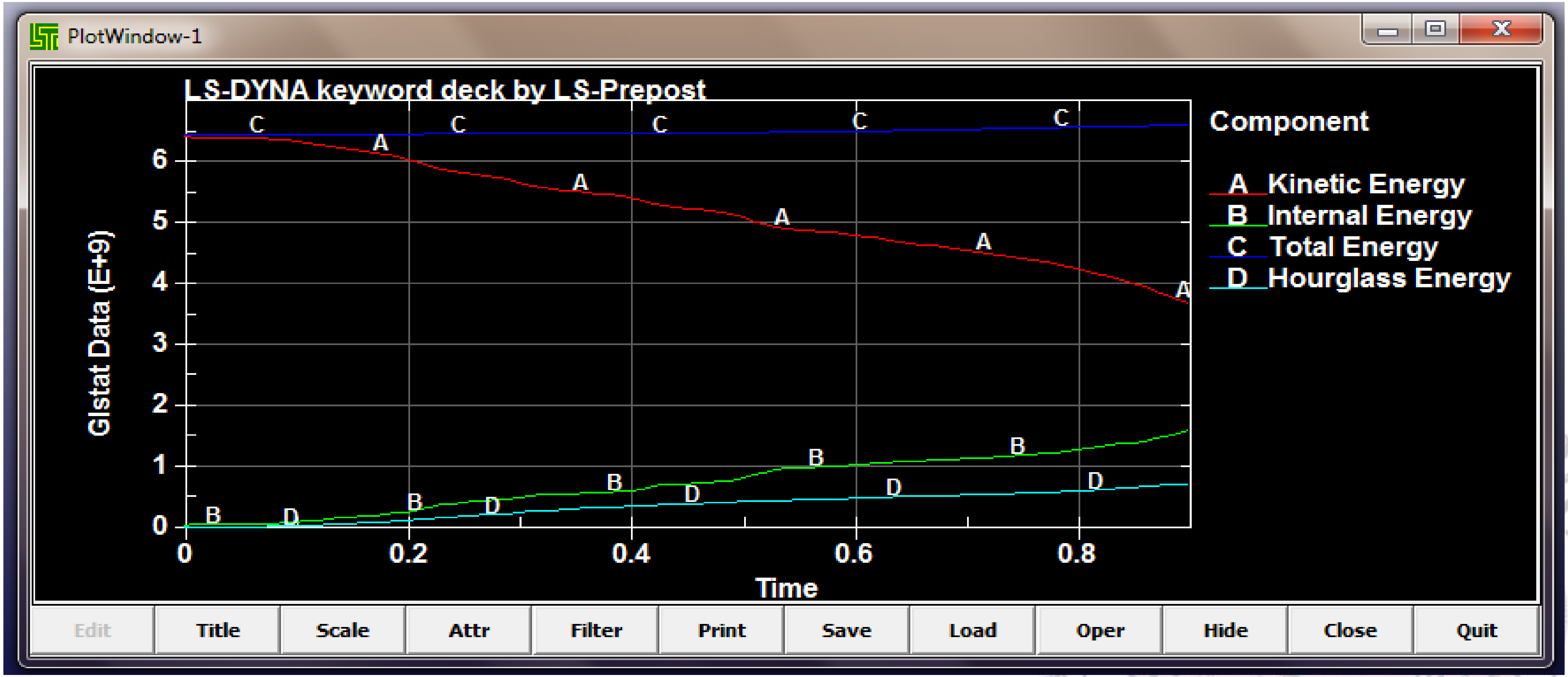
This phenomenon is amplified when a minimum number of integration points is imposed in a given element of the model.

In this way deformed configurations of the element may exist in which the points of integration do not move.

Therefore, using a single point of integration means that no variation is felt even if the element is deformed: it is a paradox since the element deforms without using energy.

At the end of the simulation this phenomenon subtracts a certain amount of energy from the entire system, thus distorting the results obtained.

Hourglass energy



For example….

Validation process – practically application

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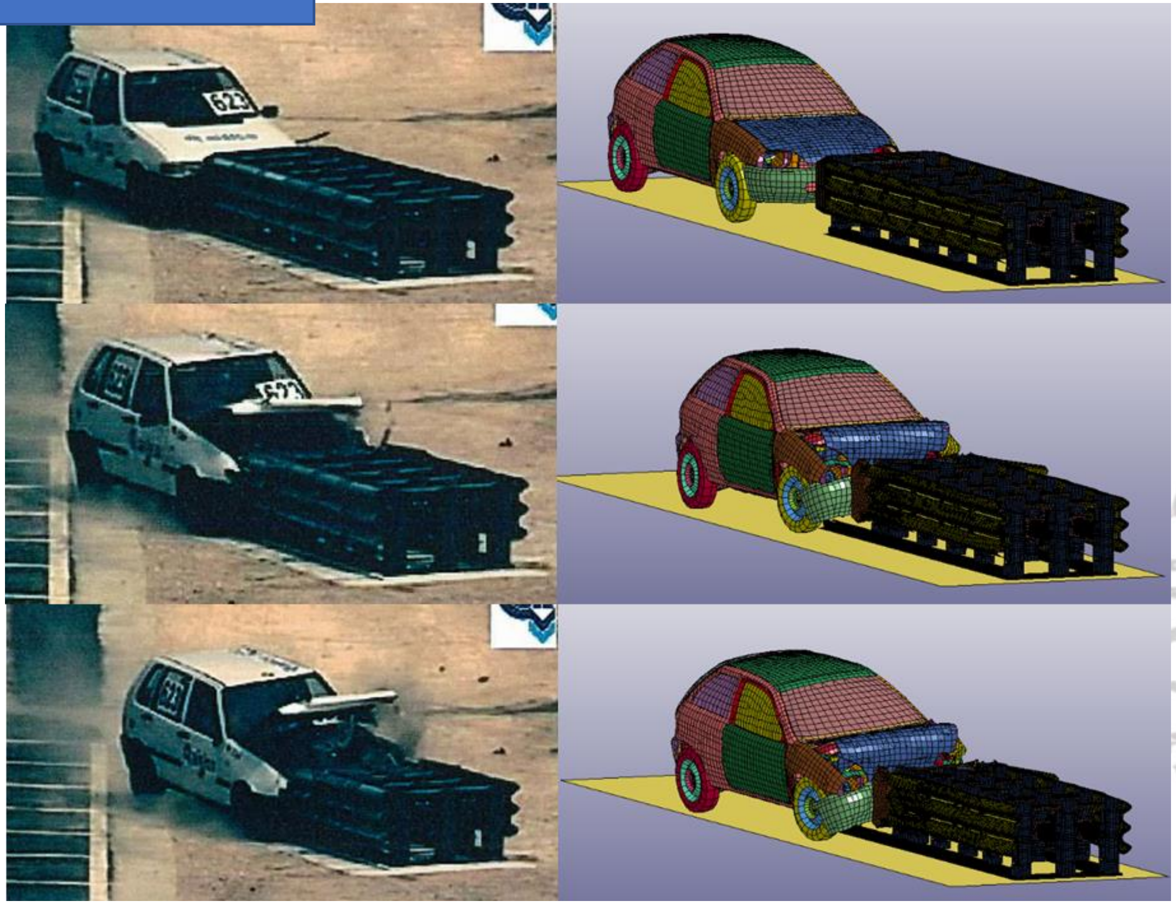
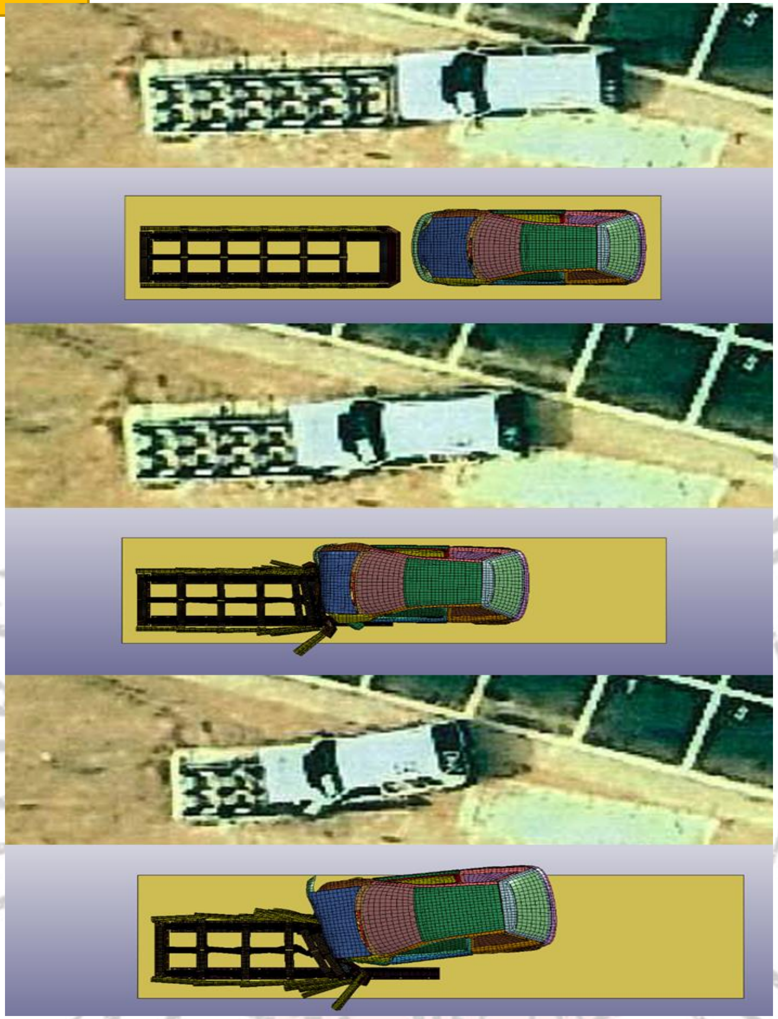
FRONTAL COLLISION WITH OFFSET

VISUAL COMPARISON





For example....

Validation process – practically application

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FRONTAL COLLISION WITH OFFSET

VISUAL COMPARISON

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Validation process – practically application

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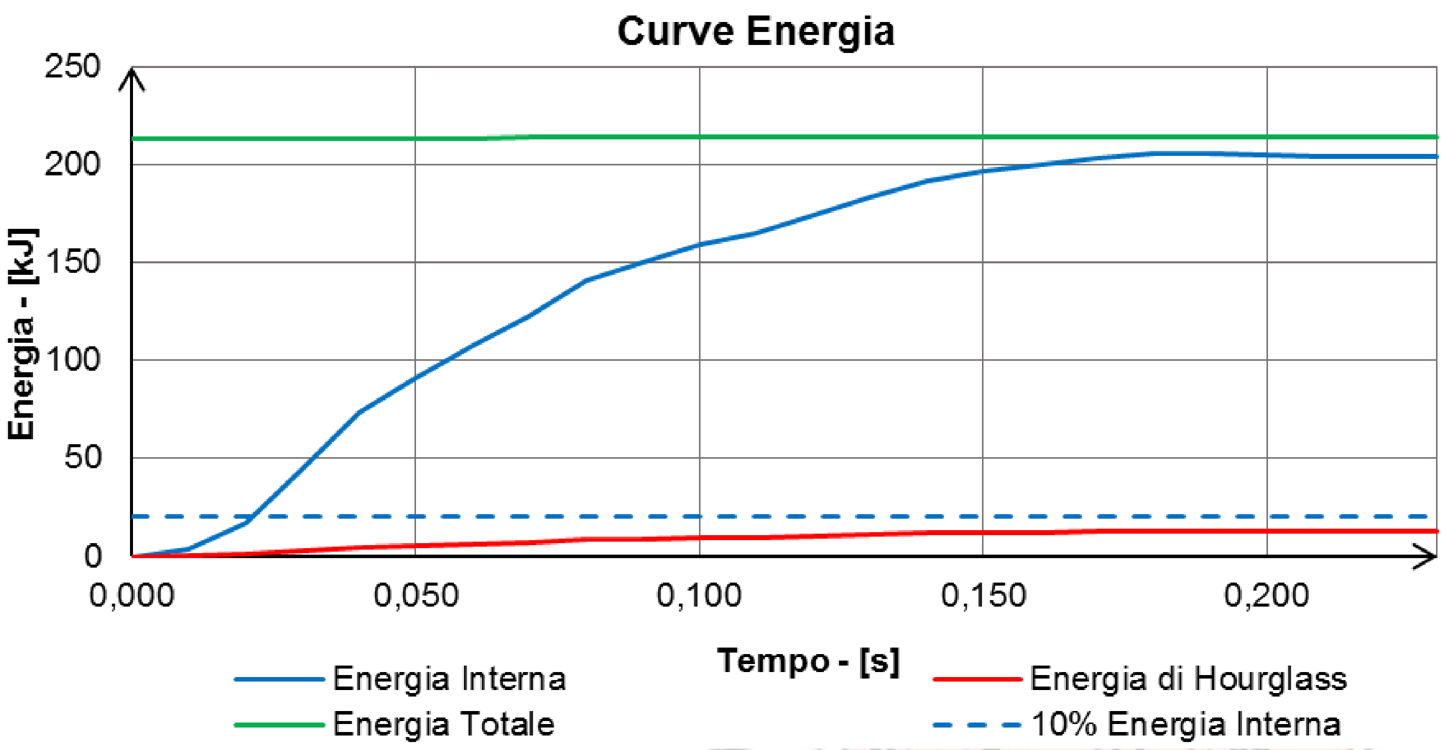
FRONTAL COLLISION WITH OFFSET

INTERNAL CONSISTENCE

Criteri di verifica della congruenza interna	*Δ %*	*Si*	*No*	*NR*
Il risultato della simulazione è fisicamente accettabile	-	✓	-	-
La variazione dell'energia totale è inferiore al 10%	***0.43***	-	✓	-
Il rapporto tra l'energia di Hourglass e quella totale è inferiore al 5%	***6.25***	✓	-	-
Massa aggiunta (al termine della simulazione la massa aggiunta deve essere inferiore al 5% della massa totale del sistema)	***4.24***	✓	-	-
Massa aggiunta (al termine della simulazione la massa della parte in cui tale fenomeno è più evidente deve essere inferiore al 10%)	-	-	-	✓
Massa aggiunta (la massa aggiunta delle parti in movimento nel modello deve essere inferiore al 5% di quella inizia lmente posseduta)	-	-	-	✓
Assenza di nodi "esplosi"	-	✓	-	-
Sono assenti elementi solidi con volume negativo	-	-	✓	-
La somma dell'energia di contatto "slave" and master" è nulla	-	-	-	✓
L'influenza della velocità di applicazione del caric o è stata considerata	-	✓	-	-
*NR = non rilevato				



For example….

Validation process – practically application

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FRONTAL COLLISION WITH OFFSET

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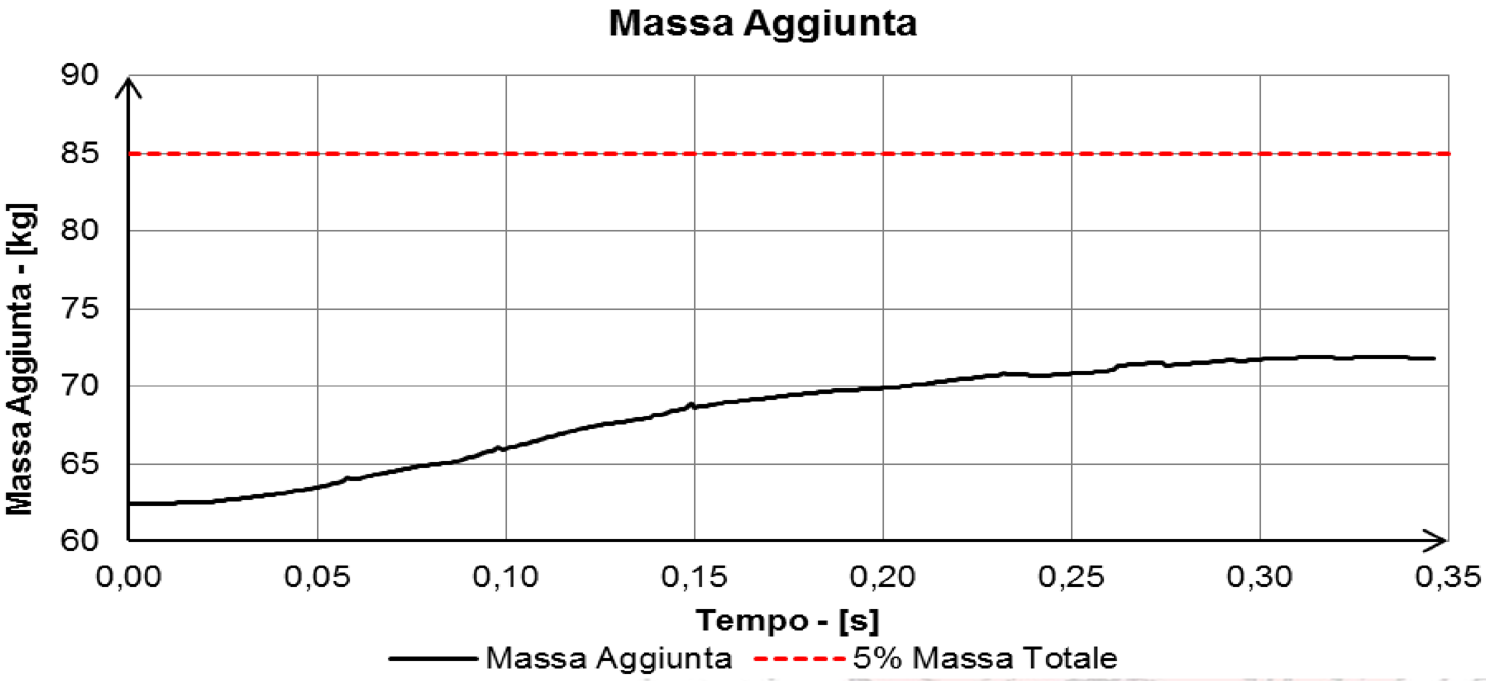
Il rapporto tra l'energia di Hourglass e quella totale è inferiore al 5%	*6.25*	✓	-	-
Massa aggiunta (al termine della simulazione la massa aggiunta deve essere inferiore al 5% della massa totale del sistema)	*4.24*	✓	-	-
Massa aggiunta (al termine della simulazione la massa della parte in cui tale fenomeno è più evidente deve essere inferiore al 10%)	-	-	-	✓
Massa aggiunta (la massa aggiunta delle parti in movimento nel modello deve essere inferiore al 5% di quella inizia lmente posseduta)	-	-	-	✓
Assenza di nodi "esplosi"	-	✓	-	-
Sono assenti elementi solidi con volume negativo	-	-	✓	-
La somma dell'energia di contatto "slave" and master" è nulla	-	-	-	✓
L'influenza della velocità di applicazione del caric o è stata considerata	-	✓	-	-
*NR = non rilevato				



For example….

Validation process – practically application

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FRONTAL COLLISION WITH OFFSET

CRITICAL BEHAVIOUR

COMPORTAMENTO CRITICO	TEST VIRTUALE/TEST REALE
Contenimento	SI/SI
Ribaltamento	NO/NO
Zona redirettiva	Classe Z1/Classe Z1
Malfunzionamento degli elementi longitudinali	NO/NO
Penetrazione di parti all’interno del veicolo	NO/NO
REQUISITI GENERALI	**TEST VIRTUALE/TEST REALE**
Spostamento laterale permanente	Classe D1/Classe D1

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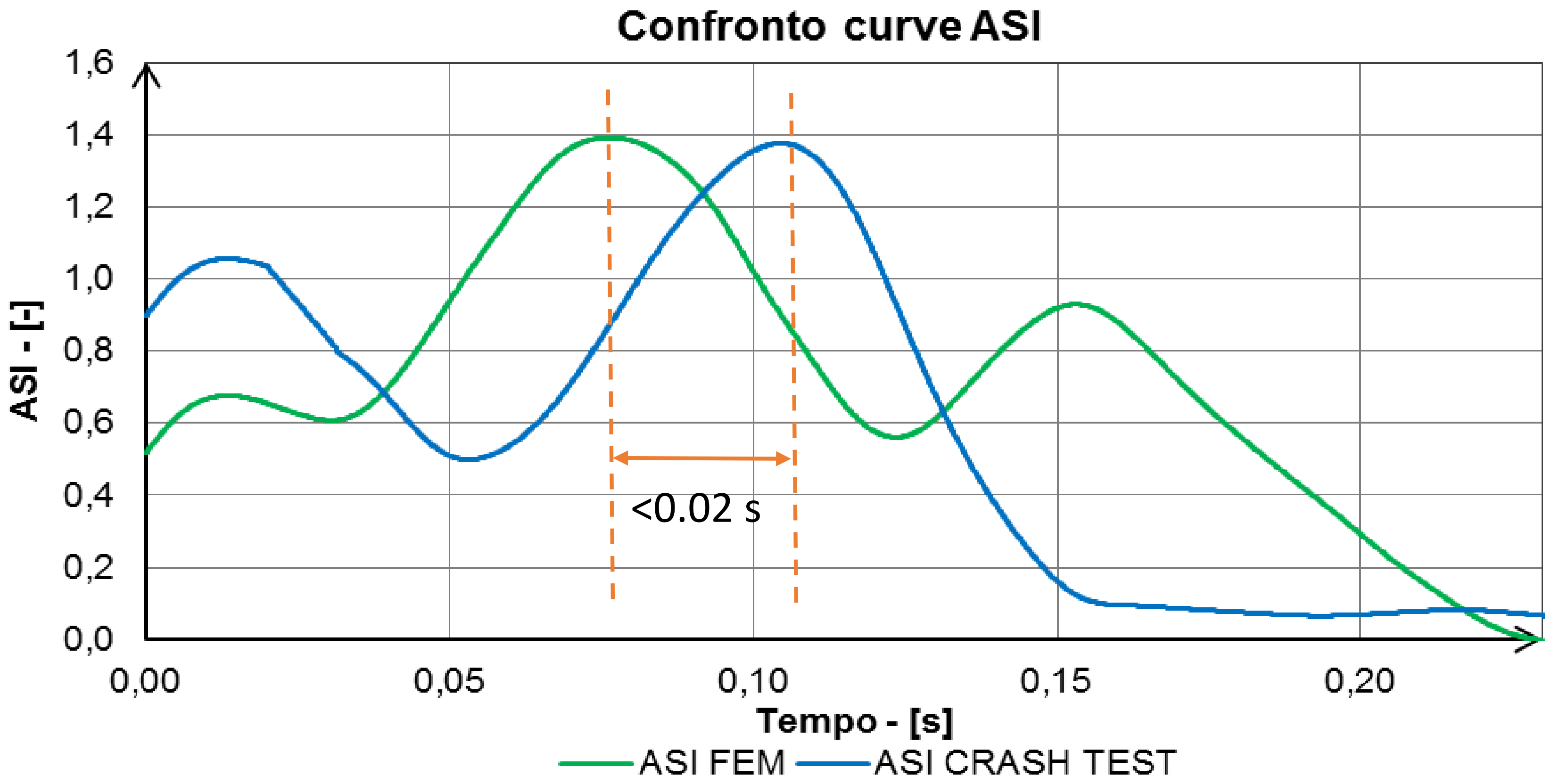
FRONTAL COLLISION WITH OFFSET

ASI COMPARISON



For example….

Validation process – practically application

pr EN 1317-5

FRONTAL COLLISION WITH OFFSET

VELOCITY WINDOWS CRITERIA