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Validating Material Information for Stochastic Crash Simulation Part 1: Quasi-Static Properties

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ABSTRACT

This paper describes the steps in validating material information for stochastic simulation using a quaisi-static tensile test experiment. Sources of physical noise usually present in a testing environment such as variation in material properties, geometry and boundary conditions are included as inputs to Finite Element models.

This work is carried out in the context of a research project supported by the Automotive Industry in the Midlands. The broad aim of the project is to establish a material properties validation process for crash simulation. Stochastic models of representative components and small assemblies in a vehicle structure, in addition to tensile testing of coupons, will be created and will form an essential part of the verification process. All models will be validated through experimental testing and these investigations will establish variations in material properties and the significance of dependencies such as strain rate and form induced thinning. Stochastic simulation is a CAE tool, enabling the support of robust engineering design. Robust engineering design is viewed as an essential part of automotive product development.

INTRODUCTION

Driving quality considerations into automotive product development to enable a reduction in variation in performance characteristics is essential for premium quality products. Quality considerations in design may be addressed in two ways. One way is to eliminate the sources of variation but this is often expensive and most probably not attainable. A better approach is to design products insensitive to variation e.g. to achieve design robustness in the presence of usual noise sources.

Currently, Virtual Prototyping (VP) has a pivotal role in product development across all industry sectors and especially the automotive sector. Conventional frameworks for VP such as Design of Experiment give an over idealized and distorted view of performance because they are unable to inform on representative variation. A stochastic simulation framework on the other hand overcomes this deficiency, permitting unrestricted random input to discern noise and dependent factors, and therefore, a more reliable platform to develop a robust design.

Although reasonably well established, simulation technology in product development is undergoing continuous improvements to enable it to be more effective in its application. The technology for stochastic crash simulation was introduced to the automotive sector more recently[1,2]. Following its initial introduction, this technology is being developed, enhanced and refined[3] through application to a wide range of industrially relevant crash simulation case studies. From which new analysis methods and tools are being introduced to industry and compliment those that are used already to support crash simulation e.g. LS DYNA, Hypermesh etc.

The focus of this research project is the validation of material properties for use in stochastic crash simulation, but the material properties derived will not be exclusive to stochastic simulation. Validation is a preliminary step to creating a materials verification process for wider use in automotive product development. The experimental investigations will focus on establishing important dependencies for specific steel material grades such as strain rate and forming effects[4-10] for current and future vehicle programmes. Working with supply chain and a leading UK car maker the ouput of this research, will be a system of agreed specifications to provide both with clear guidelines, as to what material information is expected from material suppliers, how to generate it and more over, how to use this information in product development, specifically crash simulation.

In implementing this research, the first step has been to identify the typical modes of behaviour observed in the structure of a vehicle during a typical crash event using CAE. Then to design representative generic component tests to replicate these different modes of behaviour and loading conditions. These component tests may be included as part of materials verification process. In parallel with this task quasi-static tensile property data has been generated, typically following the standard[11] as appropriate for a number of materials and especially DP600. From which material models have been created using a new process developed in this project[12] and hence providing the input to FEA systems. High velocity tensile property data is currently being acquired using state of art testing equipment and the technology for high velocity testing is being enhanced within this project too

The next phase of the project is a sensitivity analysis which aims to identify the main phsyical and numerical property dependencies for the test configurations – components and tensile specimens - using stochastic simulation. A preliminary task to establishing dependent properties however, is to ensure adequate control over the physical boundary conditions of each test to maximise sensitivity to the properties that we seek to measure. This paper is confined to this task – a sensitivity analysis of the boundary conditions of a tensile test under quasi-static loading. Initially, error sources giving rise to variation will be identified and measured. These measurements will form the basis of the random input to stochastic models. The output variation from stochastic models will be compared with physical variation measurements and importantly, for the sensitivity analysis, dependent inputs will be discerned from noise inputs. Further, and if necessary, a reduced but representative regression model of the system – linking output to input - will be created and used to make adjustments to dependent inputs as appropriate, in order to validate the variation and accuracy between test and simulation.

Experimental Investigations

Sources of Error

The error sources giving rise to variation may be divided into three groups;

- Experimental
- Model
- Sample estimates of population charateristics

Experimetal error may include all physical sources of variation such as machine and measuring system inaccuracy, operator, environment as well as properties of the structure under test. Model variations are numerical specific, for example, mesh design, element type and others. Presently, model variations will not be considered in this task but follow on from the boundary condition sensitivity analysis.

Error State Analysis

A description of all error sources are crucial to formulating the analysis problem correctly and this task is probably the most important one. Designing a model for random input follows on from this task. Error states identified are shown in the table 1 below.

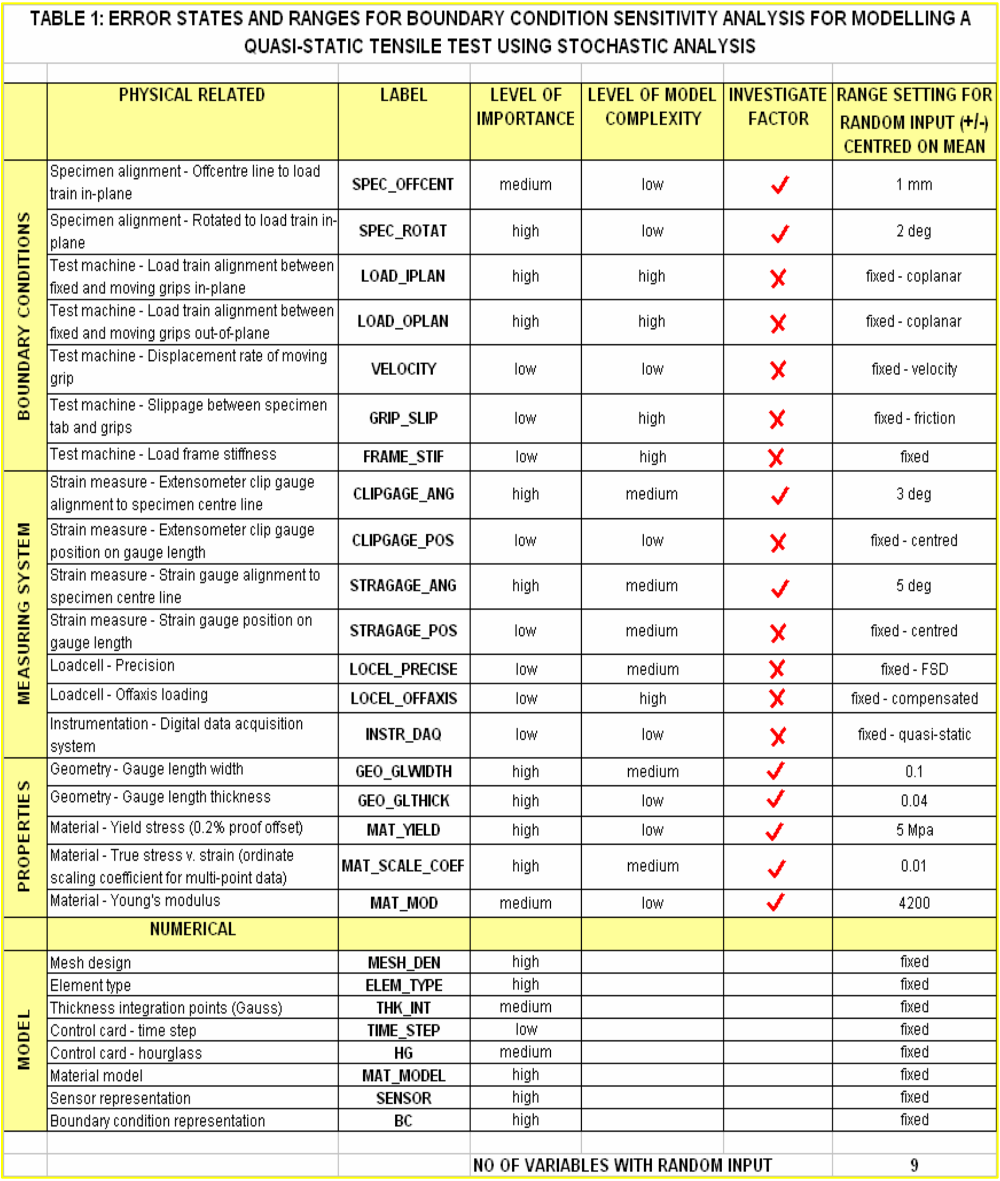


TABLE 1: ERROR STATES AND RANGES FOR BOUNDARY CONDITION SENSITIVITY ANALYSIS FOR MODELLING A QUASI-STATIC TENSILE TEST USING STOCHASTIC ANALYSIS

	PHYSICAL RELATED	LABEL	LEVEL OF IMPORTANCE	LEVEL OF MODEL COMPLEXITY	INVESTIGATE FACTOR	RANGE SETTING FOR RANDOM INPUT (+/-) CENTRED ON MEAN
BOUNDARY CONDITIONS	Specimen alignment - Offcentre line to load train in-plane	SPEC_OFFCENT	medium	low	✓	1 mm
	Specimen alignment - Rotated to load train in-plane	SPEC_ROTAT	high	low	✓	2 deg
	Test machine - Load train alignment between fixed and moving grips in-plane	LOAD_IPLAN	high	high	✗	fixed - coplanar
	Test machine - Load train alignment between fixed and moving grips out-of-plane	LOAD_OPLAN	high	high	✗	fixed - coplanar
	Test machine - Displacement rate of moving grip	VELOCITY	low	low	✗	fixed - velocity
	Test machine - Slippage between specimen tab and grips	GRIP_SLIP	low	high	✗	fixed - friction
	Test machine - Load frame stiffness	FRAME_STIF	low	high	✗	fixed
MEASURING SYSTEM	Strain measure - Extensometer clip gauge alignment to specimen centre line	CLIPGAGE_ANG	high	medium	✓	3 deg
	Strain measure - Extensometer clip gauge position on gauge length	CLIPGAGE_POS	low	low	✗	fixed - centred
	Strain measure - Strain gauge alignment to specimen centre line	STRAGAGE_ANG	high	medium	✓	5 deg
	Strain measure - Strain gauge position on gauge length	STRAGAGE_POS	low	medium	✗	fixed - centred
	Loadcell - Precision	LOCEL_PRECISE	low	medium	✗	fixed - FSD
	Loadcell - Offaxis loading	LOCEL_OFFAXIS	low	high	✗	fixed - compensated
	Instrumentation - Digital data acquisition system	INSTR_DAQ	low	low	✗	fixed - quasi-static
PROPERTIES	Geometry - Gauge length width	GEO_GLWIDTH	high	medium	✓	0.1
	Geometry - Gauge length thickness	GEO_GLTHICK	high	low	✓	0.04
	Material - Yield stress (0.2% proof offset)	MAT_YIELD	high	low	✓	5 Mpa
	Material - True stress v. strain (ordinate scaling coefficient for multi-point data)	MAT_SCALE_COEF	high	medium	✓	0.01
	Material - Young's modulus	MAT_MOD	medium	low	✓	4200
	NUMERICAL					
MODEL	Mesh design	MESH_DEN	high			fixed
	Element type	ELEM_TYPE	high			fixed
	Thickness integration points (Gauss)	THK_INT	medium			fixed
	Control card - time step	TIME_STEP	low			fixed
	Control card - hourglass	HG	medium			fixed
	Material model	MAT_MODEL	high			fixed
	Sensor representation	SENSOR	high			fixed
	Boundary condition representation	BC	high			fixed
			NO OF VARIABLES WITH RANDOM INPUT			9

The total number of variables identified with random input is nine, the balance are fixed runs. The error states will be described in more detail shortly together with content of the table. For those error states that have been judged important for this investigation, the next step is to obtain representative measurements.

Material Properties for Random Input

The quasi-static material properties may be fully characterised by three error sources using material type 24 in LS DYNA; these are yield stress (at 0.2% proof offset), plastic true stress-strain multi-point data and elastic modulus. These material properties are the minimum needed to create the material card and associated table (load curve) for multi-point data used in FEA, allowing random input variation to be introduced without conflicts arising between these properties. A load curve allows the yield stress to be set to zero on the ordinate and abscissa axes and defines a theoretical transition form elastic to plastic deformation. The plastic true stress-strain multi-point data therefore orginates from the origin of the stress-strain data and this may be scaled using load curve settings, enabling random input. Random input for elastic modulus may be introduced without affacting the settings of the other material property random variables.

Material Property Measurements

To determine the material property range settings for random input variables it is necessary to obtain a representative measure of variation. Sample estimates for material directional property variations taken from one coil of DP600 steel are determined, through quasi-static mechanical testing for 0, 45 and 90 degree orientation to rolling direction in a sheet product of 1.8 mm nominal gauge. Test results are shown in the three graphs (1a – 1c) below.

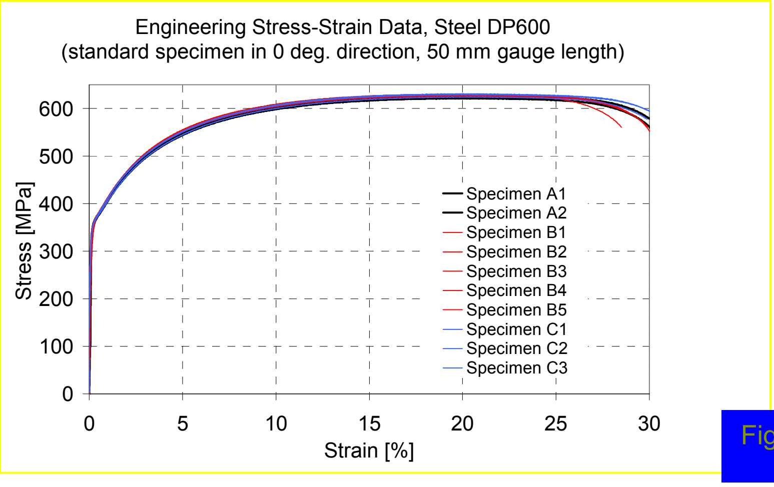


Figure 1a

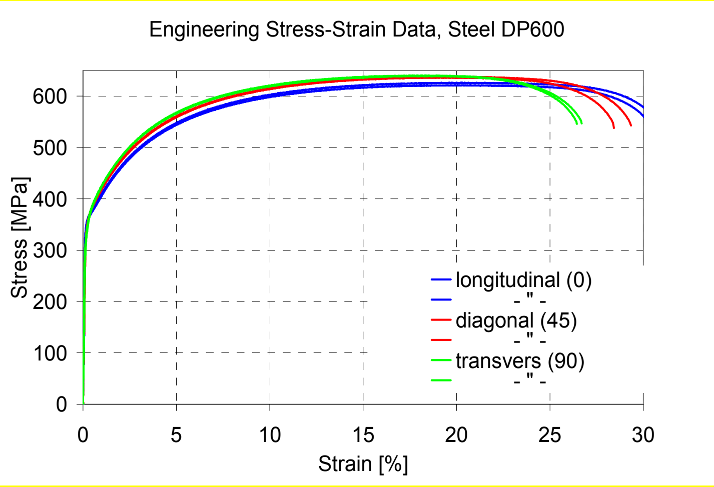


Figure 1b

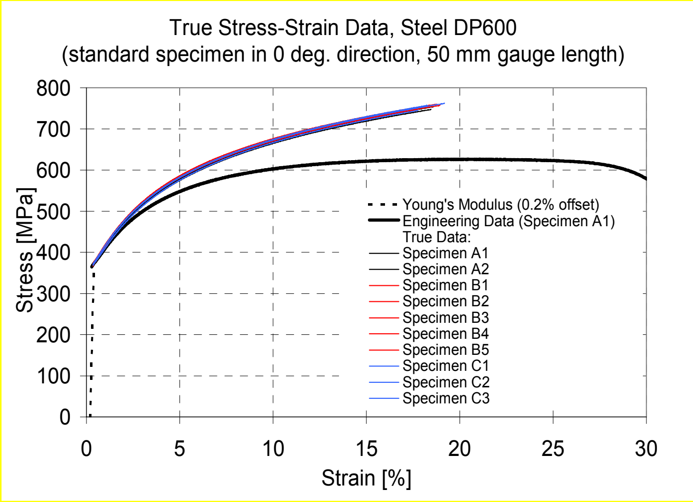


Figure 1c

These results are comparable to the results that Arcelor have produced for this material. Visually, it is observed that variation in the flow curve is almost negligable for the 0 degree orientation in which ten tensile coupons were taken from three different blanks orgininating from the same coil. But variation is slightly higher when considering the differences between directional properties 0, 45 and 90 for tensile coupons originating from just one blank. Presently, we are not concerned with property variations across different coils, which are known to be very much larger.

Material property data for 0 degree orientation are quantified in table 2 below and the range settings for random input have been determined for this material direction.

TABLE 2: DETERMINATION OF RANGE SETTINGS FOR RANDOM INPUT					
Specimen ID	**Yield Stress (Mpa)**	**Eng Strain at UTS (%)**	**Eng Stress UTS (Mpa)**	**True Strain at UTS (%)**	**True Stress UTS Mpa)**
A1	372.6	20.44	626.3	18.60	754.3
A2	369.1	20.28	621.5	18.46	747.5
B1	368.8	20.64	630.1	18.76	760.2
B2	374.5	20.86	626.9	18.94	757.6
B3	370.6	20.19	628.8	18.39	755.8
B4	374.8	19.49	626.3	17.81	748.3
B5	369.5	19.42	629.9	17.75	752.2
C1	369.9	19.43	624.2	17.76	745.5
C2	373	20.02	630.8	18.25	757.1
C3	372.5	21.15	629.1	19.18	762.1
RANGE (TOTAL)	6.000	1.72	9.30	1.43	16.62
MEAN	371.5	20.2	627.39	18.4	754.1
STDEV	2.429	6.890	1.254	2.350	1.763
RANGE SETTING (+/-)	5	14	3	5	4
ORDINATE SCALE COEFF (+/-)					0.009
ABSCISSA SCALE COEFF (+/-)				0.511	

One of the ten plastic true stress-strain multi-point data curves will be selected as a reference curve to apply a scaling tolerance to the ordinate and abscissa axes and enable random input. The curve lying more central for yield point, UTS and n value, in that order of priority will be selected as the reference curve. This is specimen number B3. Range settings for all other error sources described in table 1 have been determined by measurement and these are listed under the column range settings for random input centred on the mean.

Boundary Conditions and Measuring System

For the DP600 material tested and exhibiting very low variation, in the authors' past experience, the boundary conditions and measuring system are thought to exert the strongest influence on the error which gives rise to the variation measured. There could be a strong argument against applying variation to the materials properties because the variation measured is so low. We have recourse to run the experiment with fixed settings for material properties.

Design of Models for Random Input to Boundary Conditions

Design of model of a tensile specimen under quasi-static loading is shown in the figure 2 below with constraints applied.

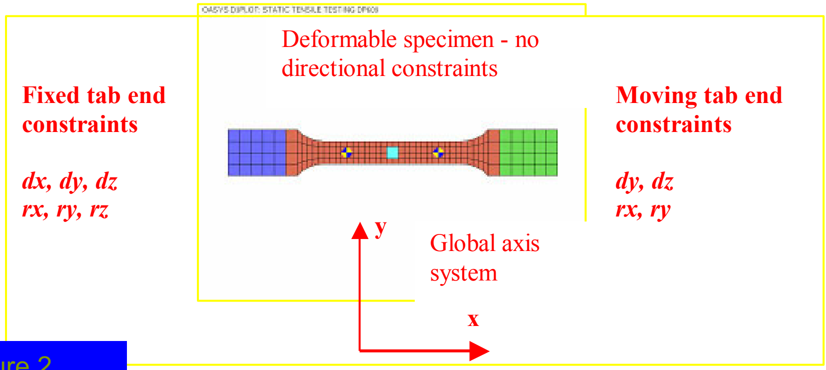


Figure 2

The interfaces between machine system and specimen define the boundary conditions of the test and these are the error states to be investigated. For example, alignment of deformable specimen between fixed grip and load introduction at moving grip. The load path between fixed and moving grip will remain coplanar in this study. Load is introduced to specimen by a fixed displacement rate for low speed testing.

Random input for specimen offset parallel to centre-line of specimen - labelled **SPEC_OFFCENT** is shown in figure 3a. **SPEC_OFFCENT** may be applied by TRANSL under *DEFINE_ TRANSFORMATION and is applied relative to the local axis system created on the centre line of specimen. The range setting given in table 1 for this error state is +/- 1mm.

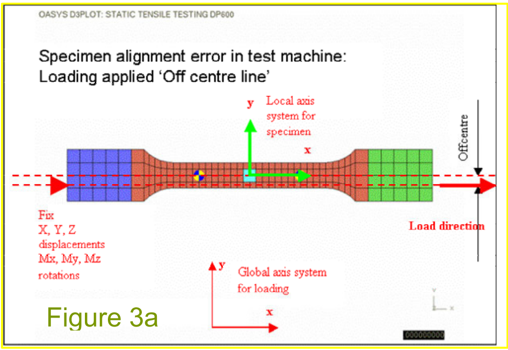


Figure 3a

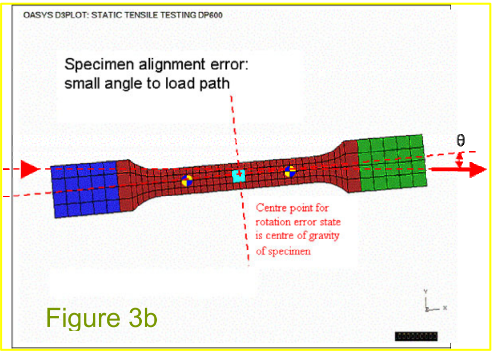


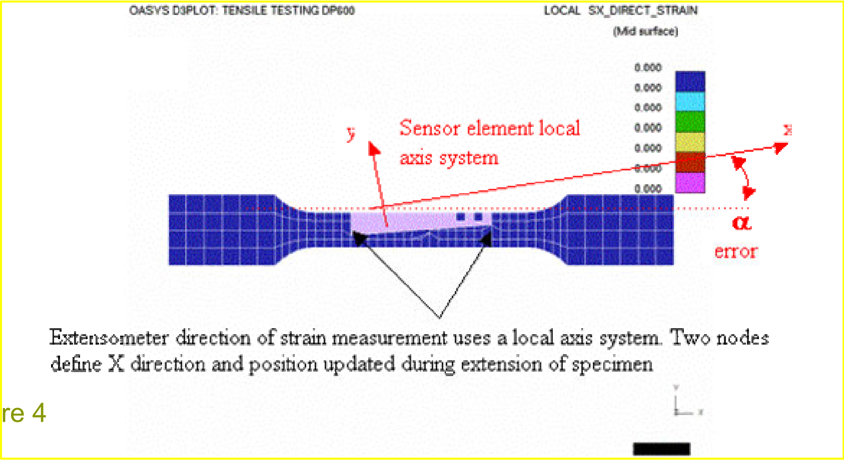
Figure 3b

Random input for specimen rotation to load path is shown in figure 3b - labelled **SPEC_ROTAT**. **SPEC_ROTAT** is applied by a small positive and negative rotation about the specimen centroid. In implementation, ROTATE may be applied using *DEFINE_ TRANSFORMATION and must be applied relative to the local axis system on the centre line of specimen. The range setting given in table 1 for this error state is +/- 2 degrees.

Quasi-static displacement is introduced to the specimen though a node with mass connected to the spring/damper. This arrangement provides a load cell to measure the force applied. The load train between fixed and moving grip always remains coplanar and the load will always be measured relative to the global axis system. Loading remains a fixed value, there is no error state definition for this variable.

Design of Models for Random Input to Measuring System

The placement of a contacting device (extensometer clip gauge) on the deformable specimen to measure strain over a nominal 50 mm gauge length will lead to measurement error through inaccurate placement by the machine operator. Random input for the clip gauge error refers to the alignment of clip gauge to the centerline axis of the specimen and is labelled **CLIPGAGE_ANG** in table 1**.** This error state is independent of specimen alignment to load path between grips, see figure 4. The range setting given in table 1 for this error state is +/- 3 degrees.



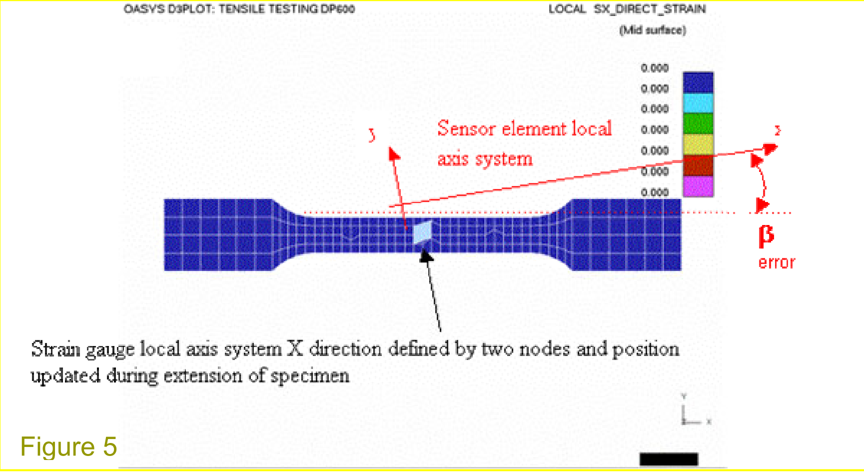
Extensometer direction of strain measurement uses a local axis system. Two nodes define X direction and position updated during extension of specimen

Figure 4

Two nodes will be displaced off the centerline axis in (Y) in the plane of shell using a local axis system e.g. *DEFINE_COORDINATE_NODES which is unique to this device; the coordinate system will be updated during large deformation. A thin elastic strain gauge sensor element is introduced on the shell mid-plane connecting four nodes in the specimen as shown in figure 4. The local axis system is also necessary for post-processing the results to obtain the effect of this error state in the correct orientation. The properties of the sensor element are typically elastic Modulus value 1000 MPa (*200 times smaller than modulus of steel*), thickness 0.001 mm, one thickness integration point, one mid-plane shell element integration scheme (equation (2) LS DYNA formulation). Use of *MAT_ELASTIC material model.

Outputs for the clip gauge sensor element are displacement X and direct strain X using outputs from shell and two nodes relative the local axis system of sensor element, see figure 4. In conducting these tests in the real world there is a requirement to measure very small elastic strain and large plastic strain to high accuracy – note strain at yield point is 0.2% offset (linear strain) whereas plastic engineering strain may typically reach 20% at the onset of neck point and 35% at failure. The output frequency in THIS required for the simulated data in THIS is therefore 2E-5 to capture the transition zone from elastic to plastic deformation with high resolution.

A strain gauge sensor is proposed in addition to the clip gauge because there is need to compare the effect of the error state of this sensor with the clip gauge device on measurement of direct strain, see figure 5. The error measured for placement of such small strain gauges (~ 6 mm in length) on a batch of specimens being prepared for high velcoity testing() is +/- 5 degrees and this is the range setting used as shown in table 1 and labelled **STRAGAGE_ANG**. This error is almost twice that measured for the clip gauge positional error. It is essential to understand what effect this large error source has in a quasi-static tensile test to assist interpretation in high velocity testing, and establish if better control over positioning must be implemented. The principles of modelling this error state are the same as described for the extensometer clip gauge.



Sensor element local axis system

Strain gauge local axis system X direction defined by two nodes and position updated during extension of specimen

Figure 5

TABLE OF RANDOM INPUTS

For the range settings prescribed in table 1, the next step is to generate a table of random input data which will be introduced to the solver for the nine indepedent random input variables. Initially, it is necessary to determine the number of runs needed to conduct robust statistical analysis to establish cause and effect using the output-input data. For large scale simulations containing many random input variables > 50, then the number of runs is at a premium. Simulation of a tensile test containing nine independent random inputs is considered a small scale analysis even though the loading speed must not exceed 100 mm/s in the explicit solution process to simulate quasi-static loading.

The number of runs may be estimated using two simple criteria. The first is after Doltsinis[1] et. al. and proposes a minimum number of runs which must be greater than (n + 1), where n is the number of independent random input variables. But he suggests (n + 1)m, where m is > 1, typically 4 or higher to attain very stable statistical results for analysis. Therefore using n = 9 and m = 4, we arrive at 40 runs of random input data.

The second approach is based on our own experience in applying this technology. Initially, the number of different modes of behaviour must be estimated. For example, angular boundary conditions involving a positive and negative random input error usually lead to bi-modality. For n modes of behaviour expected in the output then we should create 30n runs of random input data. The number 30 is driven by central limit theorum in statistics, where at least 30 samples are recommended to validate a normal distribution. It is implied that a normal distribution model fits the output data in each mode of behaviour. Although the fit of the output data to a normal distribution model it is not essential, it does influence the statistics that are applied. Our hypothesis is that at least two modes of behaviour will be present in the output data, requiring therefore 60 runs of random input data. In this analysis 100 runs of random input data will be generated. An example of the typical layout of random input data is shown in table 3 below. The columns identify the variables for random input whilst the rows identify the random input data corresponding to each run.

Table 3

TABLE OF RANDOM INPUT DATA

DISTRIBUTION MODEL FOR INPUTS = UNIFORM

		BOUNDARY CONDITIONS		MEASURING SYSTEM		PROPERTIES				
	RUN No.	SPEC_OFFCENT	SPEC_ROTAT	CLIPGAGE_ANG	STRAGAGE_ANG	GEO_GLWIDTH	GEO_GLTHICK	MAT_YIELD	MAT_SCALE_COEF	MAT_MOD
TOLERANCE RANGE		+/- 1 mm	+/- 2 deg	+/- 3 deg	+/- 6 deg	+/- 0.10 mm	+/- 0.03 mm	+/- 5 MPa	+/- 0.01	+/- 4200
MIDPOINT	0	0	0	0	0	12.50	1.8	370.6	1	205000
UPPER_BOUND	1	0	0	0	0	12.60	1.83	375.6	1.01	209200
LOWER_BOUND	2	0	0	0	0	12.40	1.77	365.6	0.99	200800
MONTECARLO SAMPLES	3	-0.140	0.967	-1.510	-1.159	12.532	1.803	375.3	0.200	202638
	4	-0.839	0.376	-2.114	1.046	12.537	1.824	371.9	0.808	206001
	101	0.9183	0.265084	0.490	-0.979	12.484	1.783	371.1	0.752	207151
	102	0.8390	-0.39668	-1.381	3.253	12.560	1.829	366.4	0.856	201721

Features of the data table include three runs numbered 0, 1, 2 which contains fixed values, these are nominal, upper and lower bound range settings for the properties only. The boundary condition fixed run values are set to zero. These fixed value settings enable a comparison between deterministic and stochastic data. Finally, a quality audit check of the random input data is carried out to validate the random data before applying the data, using the methods and tools derived in IARC.

DATA PROCESSING & TABLE OF OUTPUT DATA

Output data will be organised in two separate tables. One table will consist of charactersied output data e.g. yield stress, UTS, strain at UTS etc, and will follow a similar format to the table of random inputs - columns identify the output variables and rows identify the random input data corresponding to each run. The other table will consist of multi-point data - where columns identify the different run numbers together with force (or stress) and the rows identify displacement related data such as strain.

Fast TCF tool available in Oasys T/HIS will be used to extract the multi-point data to populate the two output data tables. These raw data consist of the force output from loadcell, nodal displacements and direct strains from clip gauge and strain gauge.

The various engineering and true stress-strain quantities are computed from the raw multi-point data to populate one of the two tables. This data is characterised following the method[12]. The charactersied data populates the other output data table.

DATA ANALYSIS

Use of graphs and conventional statistical tests that had been applied previously in the devlopment of this technology in the industrial case studies will be used to analyse this data. The research questions that will be addressed in conducting the analysis in the following order are:

1. Is the nominal response the most likely response ?
2. Can we apply parametric statistics to characterize output data
    a. is more than one mode of behaviour present ?
    b. does the data fit a normal distribution model ?

3. Quantify central tendency (e.g. mean, median or mode) and magnitude of error (variability)
4. How does variability of simulated and experimental data compare ?
5. How does accuracy compare ?
6. Which factors contribute most to error (discern noise and dependent factors) ?
7. Can we rank the dependent factors in terms of their highest significant using an alpha significance level of 5% ?
8. If necessary can we reduce the error without additional cost or added complexity in testing ?

The deliverable will be a test specification document detailing process and tolerance requirements for testing and characterising material property data under quasi-static load conditions for use in FEA crash simulation systems.

Summary and Conclusions

Presently, a model of the quasi-static tensile test has been developed for random input and tested using nominal (midpoint), upper and lower bound values, respectively, run numbers 0, 1, 2 and the results have been judged satisfactory.

It is important to recognise that the conlusions to be drawn on completion of this study will relate directly to the ranges set for each random input variable. Generalising the results beyond these ranges tested is not advisable.

This process described in this document should be seen to be generic in its application to all test configurations being considered to validate material properties for crash simulation as part of the materials verification process.

Models have been designed for all test configurations - components and coupons at for high and low velocity and are currently being developed to include random input.

From this research project new analysis tools and processes have been developed to conduct stochastic analysis, for example, a statistical analysis workbook together with high level and detailed flow charts containing the information needed to prepare, conduct, analyse and conclude a stochastic simulation.

Further, the new knowledge arising from this research work is being distilled into a knowledge Management System currently being developed in a sister project.

This research project is still open to enage more suppliers especially those based in the West Midlands.

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