Characterising performance of automotive materials at high strain rate for improved crash design

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Abstract. This paper investigates the effect of specimen geometry on the measured dynamic mechanical properties of a high strength sheet steel material derived from tensile testing at 15m/s on a high speed servo-hydraulic test machine. In this study, stochastic modelling is used extensively to support experimental investigations. The current objective is to develop a tensile specimen design and test procedure, which more closely matches the capabilities of the new IARC high speed test machine, to enable accurate and precise measurement of tensile mechanical properties over a range of strain rates up to 600 s^{-1}.

1. INTRODUCTION

An improved understanding of the behaviour of automotive materials at high velocity is driven by the challenges of diverse crash legislation and competition amongst car manufacturers. The strength hardening effect of sheet steel under dynamic loading is widely reported in academic literature and is also recognized in industry. New advanced high strength steels are seen to be increasingly attractive in those parts of the body-in-white with demanding performance requirements leading to improved vehicle crashworthiness[1] and a potential for weight reduction. Design for performance must be matched with reliable material data as a basic input to simulation tools. This requirement is driven by the increasing sophistication of vehicle crash models in their numerical description. Uncertainty in the reliability of high speed tensile test data increases with strain rate and tensile data derived from strain rates as low as $10s^{-1}$ can exhibit marked variability[2]. The cost of generating such data is also variable; in general, it is high. In crash design the strain rate dependent properties of sheet steel products must be determined accurately in the performance range of interest to end users. In response to this, this project is concerned with a refinement and standardization of current testing, characterization and validation processes, leading to the economic generation of reliable strain rate dependent material data for use in crash simulation based design.

Investigations into existing full vehicle crash models and component based models as part of this project, suggests strain rates can reach on average $50s^{-1}$ during global deformation of the structure, whilst in component based models, local strain rates deformations may reach $500s^{-1}$. The strain range of interest in the tensile curve is from yield point to maximum stress. This identifies the performance range of interest to the end user for generating reliable high speed tensile data.

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2. EXPERIMENTAL INVESTIGATIONS

2.1. Sources of Error

The figure 1 shows ten engineering stress strain curves derived from tension tests at low speed for a sheet steel product taken from the same coil, and tested in a common direction. The data appears smooth and continuous exhibiting low variability. For the material tested, yield point is measured at 0.2% proof offset and maximum stress occurs at about 20% under quasi-static load. High accuracy and precision in deriving point properties in the range of interest from yield point to maximum stress is expected from such smooth data. Such low performance variability could not be achieved in high velocity testing due to the effects of various error sources, which amplify variability.

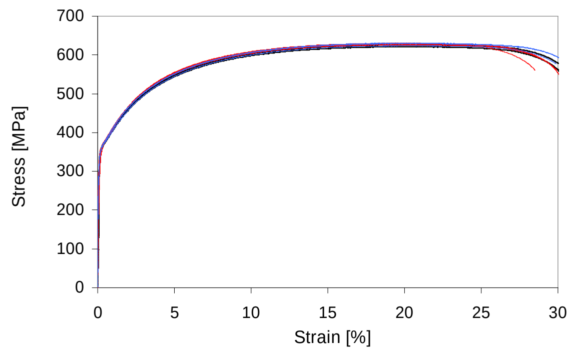

Figure 1. Engineering stress-strain test curves for steel tested in rolling direction (50mm gauge length[3]).

Sources of error in high velocity test data may be attributed to test machine type, inappropriate test controls, inertia, system of measurement, specimen design and the interpretation of raw test data.

2.2 Experimental Equipment

A servo-hydraulic high speed test machine[4] has been procured to support this research project at the IARC. The test machine has an actuator velocity capable of delivering 20 m/s under open loop control, Fast Jaw to grip specimen and data acquisition frequency of up to 5MHz. The machine control enables Fast Jaw to grip the specimen only once the actuator has reached the target velocity.

The principle of operation requires the fast jaw grip to be accelerated in the direction of the white arrow in figure 2 to reach target velocity. The knock out wedge is kicked out by a spacer rod pre-set by the test requirements, and the grips released to grab the specimen in typically 5 µs (5 x 10^{-6} sec). Sensors in the machine system include Piezo load washer in the static grip head to measure force transmitted to test machine, linear variable differential transducer to measure actuator stroke position, and accelerometer mounted on the Fast Jaw. The signals from each of these sensors are recorded on a time base. Strain gauges are placed on the specimen to measure the response in the specimen.

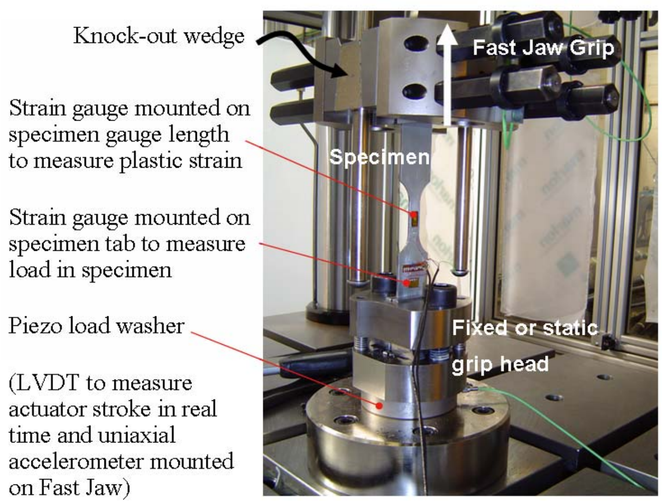

Figure 2. Tensile specimen assembled in high velocity servo-hydraulic test machine

One strain gauge placed at the centre of the gauge length and configured as a quarter bridge, measures plastic elongation to derive true strain and true strain rate. Strain gauges on the wider section of the fixed tab end, and configured as a full bridge, enable a force measurement in this 'elastically' stretched area of the specimen to derive true stress. Strain gauges are the best method to record stress-strain data at small strain when yield strength is of interest[5], but maximum strain is normally limited to 10% strain using commercial strain gauges. These specimen-based measurements may be compared with machine system placed sensors and error estimates established.

2.3 Specimen Design

Specimen design for high speed tensile testing is a function of two dependencies - machine capability and desired strain rate. To a first approximation conventional strain rate is expressed by the formula grip velocity divided by initial gauge length and this is referred to as target strain rate. The high speed tensile specimen design shown may deliver a strain rate of 600s^{-1} with an actuator velocity of 15 m/s.

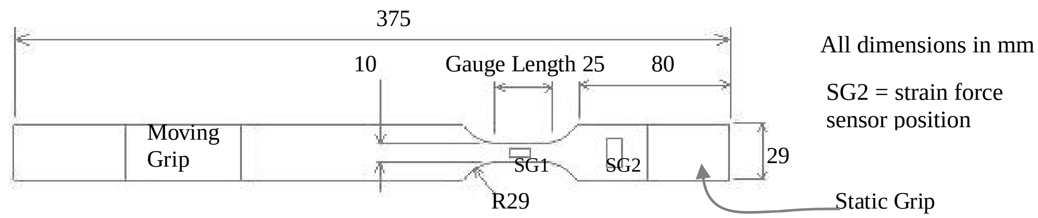

Figure 3. Specimen design for high velocity tensile test at 15 m/s

A Euronorm standard for high velocity testing is not in place, although recommendations for dynamic tensile testing of sheet steels has recently been published[5] and this was used as a guide to the current high speed specimen design.

2.3.1 Specimen Calibration

After placing strain gauges on the tensile specimen it requires static calibration, to convert the voltage signal output from both strain gauge bridge circuits to load and strain, rather than rely on conversion formula. It is therefore better to manufacture one additional specimen which will be tested to failure under quasi-static load to obtain one force-voltage and one strain-voltage calibration curve.

2.4 Typical high velocity tensile test data

The experimental data in figure 4 plots the force output against actuator position with the grip speed set to 15 m/s. The output from the machine mounted force sensor (piezo load washer) exhibits a lower ringing frequency estimated at 6kHz.

The output from the strain gauge force sensor mounted on the specimen exhibits a higher oscillating frequency of around 23kHz. The output from the specimen mounted force sensor shows a good fit through the lower frequency data measured by the machine mounted force sensor.

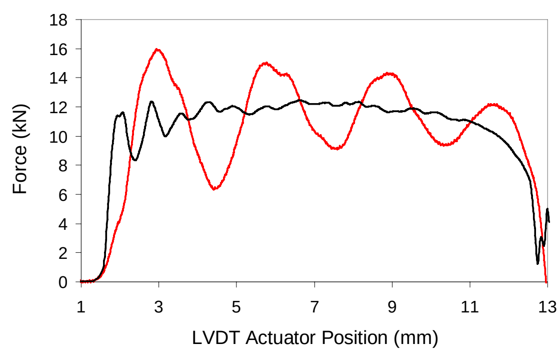

Figure 4. High speed test data generated at 15 m/s (strain rate ~ 600 s-1, DAQ frequency set to 2.5 MHz)

3. NUMERICAL INVESTIGATIONS

A three stage approach to modelling investigations has been considered, leading to a robust specimen design and test procedures which will enable accurate and precise measurement of tensile properties at high strain rate, balanced with economy. In the first stage, the frequency response of a deterministic finite element model using nominal design and quasi-static material property inputs was validated using experimental data. The result from this study was presented recently[6]. The model incorporated details of specimen, essential machine elements such as moving grips, static mass of fixed grips and all sensors used in the measurement system. Modelling investigations had focused on an improved understanding of the physical mechanisms involved in high speed tensile testing at 15m/s, quantifying errors from sensor outputs and proposing techniques to filter high frequency data output. An important finding from the first stage is the developed strain rate is more closely related to the velocity difference across the gauge length

~ typically 11m/s on average over the first ten percent strain, which delivers a markedly lower strain rate than that predicted by 15m/s grip velocity. Another finding is the strain difference measured across the strain gauge force sensor on the specimen, typically 10% at maximum tensile stress. Resulting from this first stage study there were a number of questions: How does specimen design, specifically geometry, influence the performance measures of interest? Specifically, is there a tensile specimen geometry which delivers a performance less sensitive to stain gauge sensor position on the specimen? Is it possible to reduce error by design of geometry?

3.1 Modelling approach

The second stage reported here is to investigate wider geometry variations based on the stage one model, to establish a specimen design more closely matched to the capabilities of the new test facility, and especially one which is less sensitive to noise factors in the testing environment. It is desirable to investigate specimen geometry variations such as gauge length and width, transition radius and others, and establish their effects on dynamic material property measurements obtained from high speed tests using stochastic modelling. The material data input to the specimen model uses quasi-static experimental data and this is a fixed parameter. Since material input is fixed and known, the difference between the response and material input is computed as an error. Finally, statistical correlation will be applied to confirm and rank geometry dependencies and regression relationships established where appropriate.

3.2 Modelling geometry variations

Geometry variations of interest are listed in table 1 and shown in figure 5 below. Grip length is a boundary condition which is included because it may, in combination with specimen geometry, affect performance. The performance error measures of interest are given in the table in the results section.

Table 1. Random input variables and ranges used in model

	Random Variable	Nominal (mm)	Upper Bound Limit (mm)	Lower Bound Limit (mm)	Distribution Model Applied	Number of Independent Samples
Geometric Properties	Static Grip L	34	65	34	Uniform	100
	Trans Radius	20	36	4	Uniform	100
	Gauge L	25	40	10	Uniform	100
	Gauge W	10	12.5	7.5	Uniform	100
Boundary Condition	Grip Offset	0	35	-35	Uniform	100

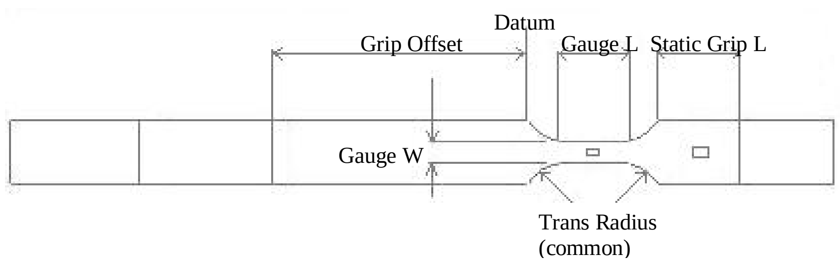

Figure 5: Definition of random geometry variables used in model

The Montecarlo method is used to generate 100 unique and independent specimen designs. Strain gauge positions are maintained centred in the gauge length and static grip length. Whilst geometry is varied for each specimen, the element size is fixed at a 1 mm square grid. A finite element model for each specimen design is created using a commercially available software tool. The resulting nominal, upper and lower bound designs are shown in figure 6.

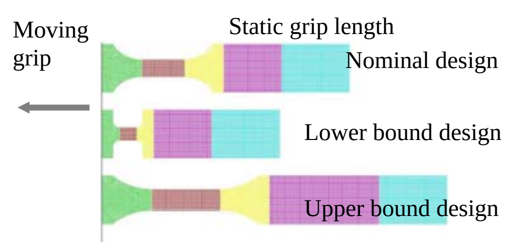

Figure 6. Models of specimen geometry variations. Moving grip length (to left of figure) and strain gauges omitted for brevity

4. RESULTS OF STOCHASTIC MODELLING

The figure 7 shows uniform elongation and position of tensile necking deformation modes are centred in the specimen gauge length for all model specimen designs. Time of necking initiation is dependent on initial gauge length. The necking in the nominal design model is consistent with high speed camera recordings taken at 100,000 fps of an experiment at 15m/s. Typical simulated raw data outputs for selected performance measures are shown in figure 8, and this will be used in subsequent data analysis.

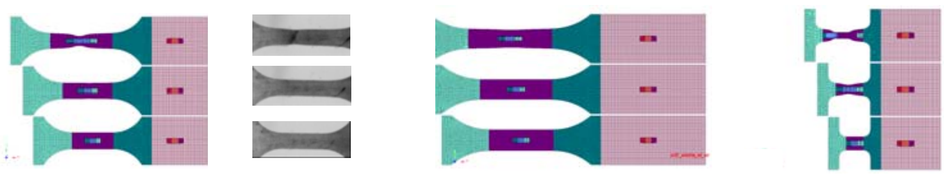

Figure 7. Verification of tensile specimen deformation modes, left figure nominal design geometry and experiment, middle figure upper bound design geometry and right figure lower bound design geometry.

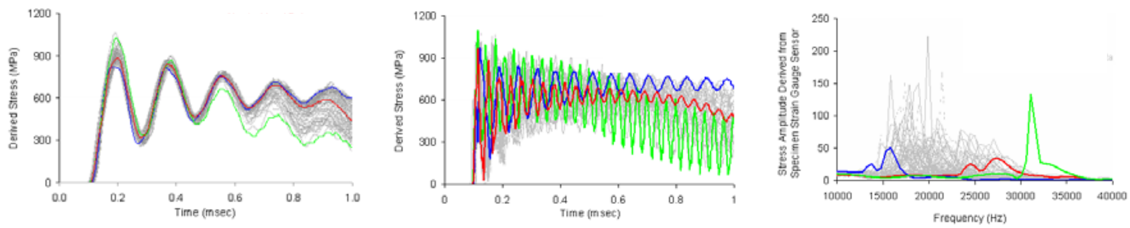

Figure 8. Left figure is derived engineering stress from machine sensor versus time (bold curves are nominal and bounded values). Middle figure is derived engineering stress from strain gauge force sensor versus time. Right figure is derived engineering stress from strain gauge force sensor versus time converted to frequency domain by FFT.

4.1 Performance measures

Performance measures of interest for analysis are identified in the table 2 below and a notation OP(no.) assigned for further reference. Difference measures OP1, OP6, OP7 and OP8 are error estimates.

Table 2. Notation for characterised performance measures.

OP1	Maximum engineering stress difference between filtered strain gauge output and orginal test result
OP2	Maximum engineering stress gradient across strain gauge normalised by max stress (eng strain range 0 to 20%)
OP3	Average engineering stress gradient across strain gauge normalised by max stress (eng strain range 0 to 20%)
OP4	FFT - maxmimum stress amplitude from strain gauge in frequency range 10 kHz and 40 kHz
OP5	FFT - frequency corresponding to maxmimum stress amplitude from strain gauge
OP6	Maximum error between derived and target engineering strain rate (eng strain range 0 to 5%)
OP7	Average difference between derived and target engineering strain rate (eng strain range 5% to 10%)
OP8	Maxmimum engineering stress difference between filtered machine sensor ouput and orginal test result

4.2 Variable ranking

Table 3. Results of eigen analysis of correlation matrix of simulated data.

Performance Ranking		Geometry Dependency					PERFORMANCE OBJECTIVE
Eigen value Proportion (%)	Eigen vector	Static Grip L	Trans Radius	Gauge L	Gauge W	Grip Offset	
31	OP7	0	2	-3	0	0	Minimise
26	OP3	0	0	0	2-3	1	Minimise
14	OP5	-3	-1	0	0	0	Maxmise
13	OP8	0	0	0	0	0	Minimise
10	OP1	0	1	0	2	0	Minimise
4	OP4	2	0	-2	-2	0	Minimise
DESIGN OBJECTIVE		Minimise	Minimise	Maxmise	Minimise	Minimise	

Legend
Correlation siginifcant above +/- 0.3
(+) ve = positive correlation
(-) ve = negative correlation
(0) No correlation (r =< 0.3)
(1) Low correlation (0.3< r =< 0.5)
(2) Moderate correlation (0.5 < r =< 0.7)
(3) High correlation (r > 0.7)

5. DISCUSSION AND CONCLUSION

Geometry input dependency is determined through correlation, and together with a statistical test of significance, verifies input dependency to each performance measure. An eigen analysis of the correlation matrix suggests the six performance measures listed in table 3 are linearly uncorrelated. Other performance measures are coupled to these. Geometry input correlation may be positive or negative as identified in table 3. Examples of positive and negative correlation are shown in figure 9.

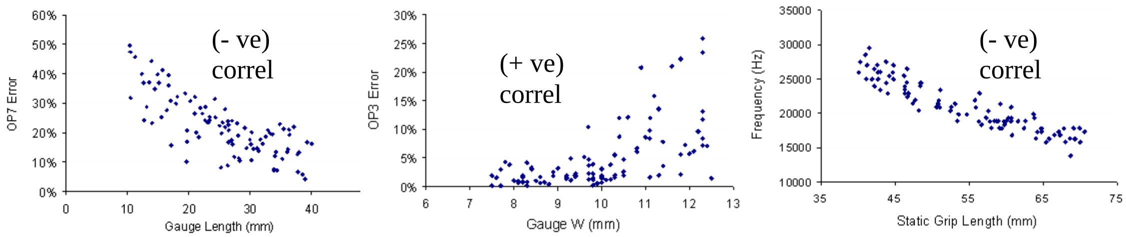

Figure 9. Left figure is highest eigen vector OP7 versus specimen gauge length, showing a negative correlation (r = -0.74). Middle figure is second highest eigen vector OP3 versus gauge length width, showing a positive correlation (r = 0.66). Right figure, OP5 is ranked third and showing a high negative correlation to static grip length (r = -0.92).

The far right column of table 3 states the performance objective – to maximise or minimise. All performance measures must be minimised (these are errors) with exception to OP5. The design objective for specimen geometry is given in the bottom row of table 3 and the requirements may be summarised as follows, taking into consideration the general recommendations of reference[5]:

Static Grip L: High negative correlation to OP5. Design objective is to minimise Static Grip L to increase frequency response (OP5) of transducer on specimen. There is however, a possibility of increasing the stress amplitude (OP4). In practice, the measured high frequency response is more damped than predicted by simulation, see figure 4. There is no measurable effect on other performance errors.

Trans Radius: Moderate and low positive correlation to performance measures OP7 and OP1, and low negative correlation to OP5. Design objective is to minimise Trans Radius to reduce performance errors OP7 and OP1, and increase OP5 (reduce frequency response). Suggest desirable practical range is 12 to 15 mm (nominal = 20mm).

Gauge L: High and moderate negative correlation to OP7 and OP4. Design objective is to increase Gauge L, but this can not override the strain rate target required, although the machine can be set to operate at a higher velocity. The point to emphasise is that error increases with smaller gauge lengths, with a typical error reaching 50% for a 10mm gauge L and reducing to 10% for a 40 mm gauge L.

Gauge W: High positive correlation to OP3 and moderate negative correlation to OP4. OP3 error reaches 30% above 10mm. Design objective is to reduce Gauge W to below 10mm.

Grip Offset: Low correlation to OP3. Design objective is to reduce Grip Offset but this is not essential.

The research work has provided guidelines which has enabled a specimen design to be developed for use with the IARC high speed test machine, to provide precise measurement of strain rate property data at strain rates of $600s^{-1}$.

6. References

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