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An improved test procedure for measurement of dynamic tensile mechanical properties of automotive sheet steels

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ABSTRACT

This paper investigates the effect of specimen geometry and test boundary conditions on the measured dynamic mechanical properties of high strength sheet steel derived from high speed tensile testing at 15m/s, using a servo-hydraulic test machine. In this study, stochastic modelling is used extensively to support experimental investigations. From the results, recommendations are proposed in detail, for an improved specimen design, and hence a robust test procedure, to generate reliable material strain rate sensitivity data for automotive sheet steels at higher strain rates, typically up to $600s^{-1}$. The recommendations proposed are expected to have broader application.

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 the industry. New advanced high strength steels are seen to be increasingly attractive in those parts of a vehicle structure with demanding crashworthiness[1] requirements, leading to reduced cost, weight and improved design-packaging efficiencies. The economics of virtual testing are driving increasingly sophisticated vehicle crash models, and hence design for improved crash performance must be matched with reliable material data as a basic input to simulation tools.

Uncertainty in the reliability of material tensile data increases with strain rate. In a round robin study[2] involving ten international testing laboratories reported in 2006, it has been shown sheet steel material tensile data derived from strain rates at $10s^{-1}$ exhibits appreciable variability.

The cost of generating material tensile data with strain rate dependency is high. A cost survey conducted as part of this study, and involving both academic and industry sources suggest a factor of typically fifty times higher than the cost to generate quasi-static tensile data to Euronorm[3] requirements.

The high cost and uncertainty in the quality of material strain rate sensitivity data is the motivation for this study. The aim is to establish recommendations for generating reliable material strain rate sensitivity data for use in crash simulation design tools, to support development of premium automotive products. This study forms part of larger body of work, which considers the requirements for the generation of strain rate sensitivity data for ferrous and non-ferrous materials, together with the processes to transform, model, and to format this data for input to crash simulation tools, and finally to validate this data in representative crash structures. This project is supported by a luxury car-maker, a number of consulting and material suppliers to the premium automotive and other transport sectors.

Design range of interest

The design range of interest is a key driver for the generation of material strain rate sensitivity data. Investigations into existing full vehicle crash models for steel structures and component crash models within this project, suggest strain rates can on average reach $60s^{-1}$ in a deforming crash structure, and in the extreme may reach $500s^{-1}$ locally in component models.

Simulated strain measurements taken from the shell surface *using the outer Gauss integration point* in the corner elements of component models can reach, typically, on average 30% effective strain in tension or compression, and occasionally exceed 100%. The strain range available in the tensile curve is from yield point to maximum stress; this is the range of *uniform plastic elongation*, and identifies the design range in the tensile flow curve available for generating material strain rate sensitivity data.

VARIABILIY IN MATERIAL TENSILE DATA

A number of high strength sheet steel products available from different material suppliers have been tested within this project. The figure 1 shows ten quasi-static raw tensile flow curves derived from one of these material suppliers sheet steel products. The specimens tested were taken from the same batch in a coil, and tested in a common direction. The flow curves obtained is typical of one class of high strength materials from different suppliers; the characteristics appear smooth and continuous exhibiting low variability in the design range of interest. For the material tested, yield point is measured at 0.2% proof offset and maximum tensile stress occurs at about 20% engineering strain. High accuracy and precision in deriving point properties in the range of uniform plastic elongation is expected from such smooth test data.

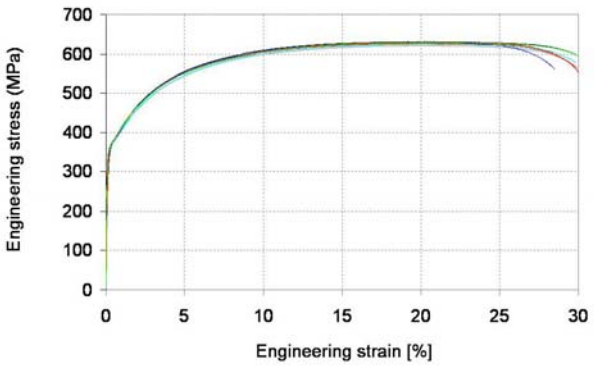

Figure 1. Derived quasi-static engineering flow curves for DP600 sheet steel tested in roll direction (50 mm gauge length / Euronorm test procedure [3]).

In high speed tensile testing however, the accuracy and precision in deriving point dynamic properties is much more difficult due to the presence of oscillation in force measurement, and capability of extensometry methods used in strain measurement on the gauge length. In high speed testing the measured dynamic properties will be influenced by the test machine system used e.g. impact bar versus servo-hydraulic and variations within each system, specimen design and the system of measurement, or more generally, test procedure.

EXPERIMENTAL INVESTIGATIONS

EXPERIMENTAL EQUIPMENT TO DERIVE MATERIAL STRAIN RATE SENSITIVITY DATA

The servo-hydraulic high speed test machine[4] at the IARC has an actuator velocity of up to 20 m/s under open loop control, 10^{-3} to 1 m/s under closed loop control, a Fast Jaw to grip specimen and data acquisition frequency of up to 5MHz. The machine control enables the Fast Jaw to grip specimen only once the actuator has reached target velocity.

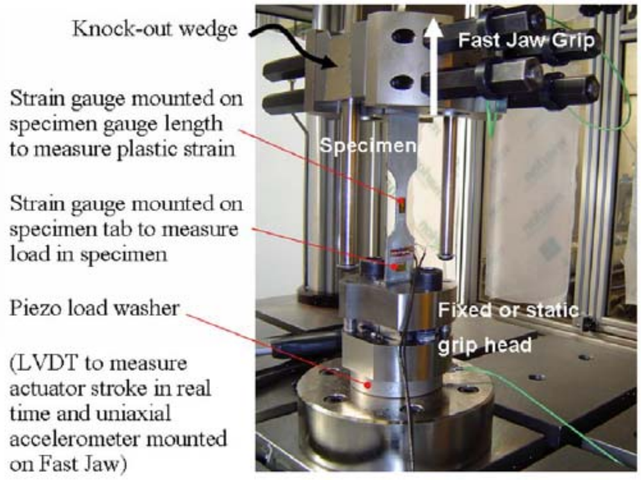

Figure 2. Tensile specimen assembled in high velocity servo-hydraulic test machine.

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. On completion of the acceleration phase the knock out wedge is kicked out by a spacer rod pre-set by the test requirements, and the sprung grips released to grab the specimen in under 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 signal from each sensor is recorded on a time base.

In addition to machine sensors, strain gauges are placed on the specimen to measure a local response. One strain gauge placed at the centre of the gauge length, and configured as quarter-bridge measures plastic elongation, to derive strain and strain rate. Strain gauges on the wider section at the static grip end, and configured as a full bridge to compensate for bending, measure an elastic elongation to derive load (or stress).

A strain gauge on the gauge length is the best method for strain measurement at small strains, especially when yield point accuracy is required at high strain rate[5][6]. However, very high measurement accuracy is normally restricted to 1% elongation, and typically adhesive, or gauge failure occurs at moderate to high plastic strain 10% to 20%.

High speed tensile 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; this will be referred to as target strain rate. The high speed tensile specimen design shown in figure 3, will deliver a target strain rate up to $600s^{-1}$ with an actuator velocity of 15 m/s. The specimen gauge length may be increased and actuator speed reduced to derive dynamic property measurements at lower strain rates.

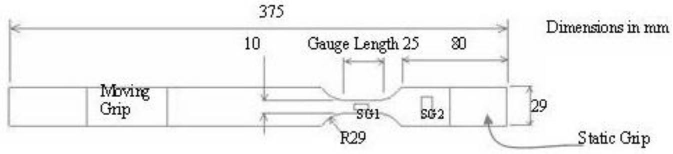

Figure 3. Specimen design for high velocity tensile test at 15 m/s (SG1 = strain gauge strain sensor, SG2 = strain gauge force sensor).

A Euronorm standard for high velocity testing is not in place, although general recommendations for dynamic tensile testing of sheet steels has recently been published[5][7] and in draft[8]. These documents were used as a guide to the current high speed specimen design and development of test procedures.

Calibrating strain gauges on tensile specimen

On completing the installation of strain gauges on a tensile specimen it requires mechanical calibration under quasi-static conditions to verify the relationship existing between voltage output and force, and similarly voltage output and strain on gauge length, see figure 4. In preparing a batch of high speed tensile specimens one additional high speed specimen will normally be made and tested to destruction in a quasi-static test machine instrumented with a clip gauge extensometer to provide calibration data.

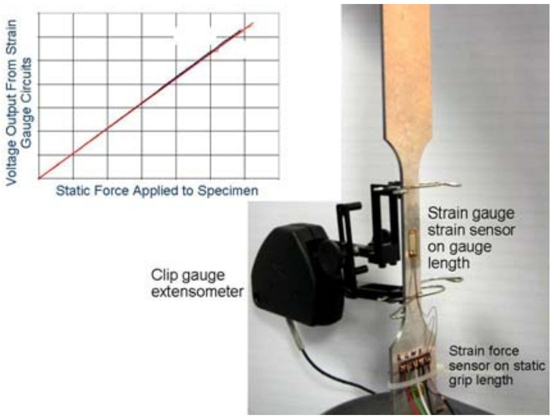

Figure 4. Quasi-static calibration.

RAW HIGH VELOCITY TENSILE DATA

Raw experimental data for a high strength sheet steel derived from a high speed tensile test at 15 m/s using the specimen design of figure 3 is shown in figure 5. The output from machine force sensor (piezo load washer) exhibits a low oscillating frequency estimated at 6 kHz and only three full oscillations develop.

On the other hand, the output from the strain gauge force sensor on specimen develops a higher oscillating frequency of just over 20 kHz, and this enables improved precision and accuracy in curve fitting, and similarly location of point dynamic tensile properties.

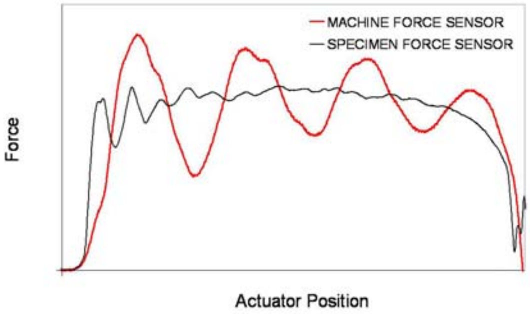

Figure 5. High speed test data generated at 15 m/s (strain rate ~ 600 s-1, DAQ frequency set to 2.5 MHz).

The higher oscillating frequency response appears consistent when testing similar high strength steels and with different thickness, using a common specimen geometry.

Tensile data derived at different strain rates

Raw high speed tensile data is generated across a spectrum of strain rates to create a set of material flow curves with strain rate dependency, see figure 6. Notice the amplitude of load oscillation increases with strain rate, and similarly the wave length of the frequency response.

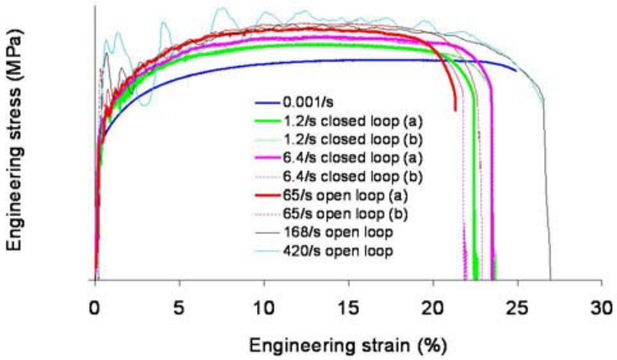

Figure 6. Raw engineering strain rate data.

Fitting model to raw strain rate data

The raw data of figure 6 is pre-processed to create true plastic data for the region of uniform plastic elongation, see upper figure 7. A surface model with three dependencies *e.g. stress, strain and strain rate* may be fitted to the raw plastic data to create a family of flow curves, see lower figure 7.

Finally, the surface model is formatted for use in a commercially available finite element code.

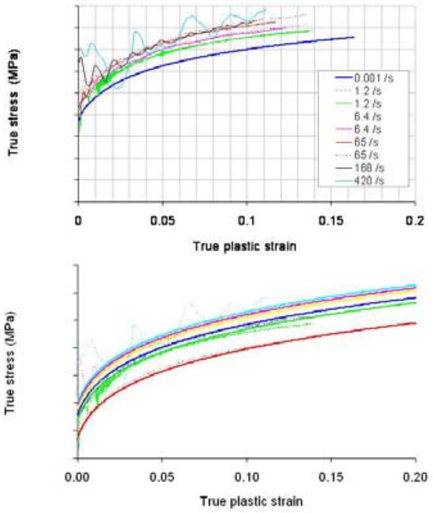

Figure 7. Raw true plastic data (above). Surface model fitted to raw true plastic data (below).

NUMERICAL INVESTIGATIONS

The purpose of modelling the high speed tensile test is to lead the development of robust test procedures in which specimen design, the measurement system and test boundary conditions are important considerations.

MODELLING APPROACH

Modelling investigations proceeded in three stages. In the first, a stochastic finite element model of the specimen used to generate the quasi-static tensile data in figure 1 together with appropriate test boundary conditions was developed. Model random variables included the system of measurement e.g. clip gauge and strain gauge sensor positions/angles on specimen gauge length, specimen alignment to load train and gauge length geometry ~ *thickness and width*. Each random variable is varied independently using the Montecarlo method and a uniform distribution model applied. The tolerance assigned to each model random variable was determined from measured values.

The material input to model is a fixed parameter and therefore one of the quasi-static material flow curves roughly centred in the experimental data set shown in figure 1 was selected. This flow curve is transformed to true plastic data and formatted for input to simulation software[10].

The result of one hundred simulations and ten experimental tests is shown in figure 8. The model and experimental data show very good agreement in terms of accuracy and precision in the strain range of uniform elongation. Although, engineering strain at maximum tensile stress (neck initiation) develops around 26%, rather than 20% as evidenced by the test results. Reducing the model element size in the gauge length to typically a 1 mm square grid delivered a result more consistent with the test data. The quasi-static model result enables improved confidence in developing a reliable model of the high speed tensile test.

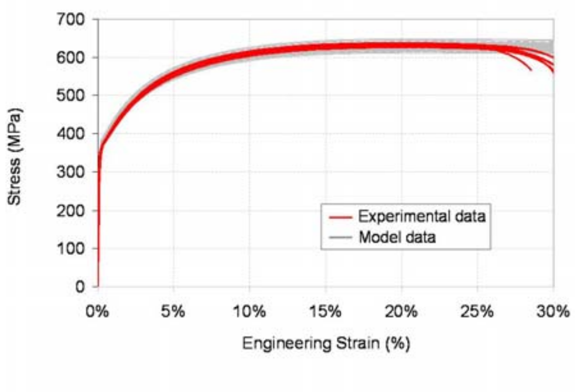

Figure 8. Compare model and experimental data derived from quasi-static tensile test.

Development of high speed model

The second step involved the development of a deterministic finite element model of the high speed tensile test at 15 m/s for the specimen geometry of figure 3. An important objective is to validate the frequency response of model sensor outputs using the high speed test result of figure 5, in preparation for the third stage stochastic analysis. The quasi-static material flow curve used in the first stage is the input to the high speed model. Importantly, since material input is known, the difference between model output e.g. derived tensile data, and material input may be directly computed as an error.

The high speed model incorporates details of specimen geometry, essential boundary conditions (machine elements such as moving grips, static mass of fixed grips) and all sensors used in the measurement system on machine and specimen; this work was reported recently[11]. The frequency response of model and experimental force measurement is shown in figure 9. The load measurement from machine force sensor is calibrated by adding mass and viscous damping to the spring element in the model. There is no damping applied to the strain gauge force sensor in the lower figure 9. The resulting amplitude of load oscillation in the model is much higher compared to the test result, although the frequency response is broadly consistent.

Preliminary findings

The findings of the second stage modelling investigation enabled an improved understanding of the mechanical mechanisms involved and likely sources of large error, in deriving tensile data from measurements made in high speed tensile testing. Techniques to filter oscillatory data output were also reviewed.

Other important findings noted; 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, therefore giving a markedly lower strain rate than that predicted by the approximation grip velocity divided by initial gauge length.

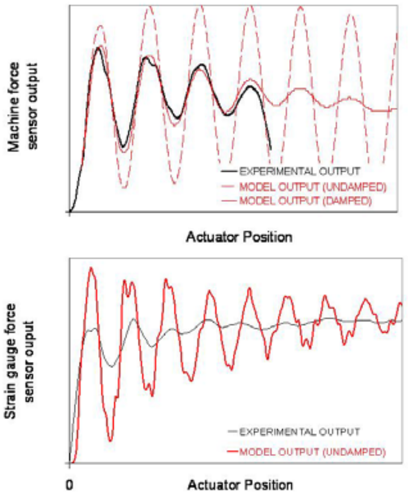

Figure 9. Comparing frequency response of force measurement between model and experiment. Upper figure output from machine force sensor. Lower figure output from strain gauge force sensor.

Resulting from this second stage study there are a number of questions: How does specimen geometry influence the dynamic mechanical property measurements (or performance measures)? Is it possible through design of geometry to reduce the amplitude of load oscillation measured from the force sensor and/or increase its frequency response?

MODELLING GEOMETRY VARIATIONS

The third stage reported in detail herein is to investigate specimen geometry variations for the high speed test conducted at 15 m/s using stochastic modelling. The deterministic model of stage two will be used for this purpose, and the geometry described in figure 3 will be referred to as the nominal design.

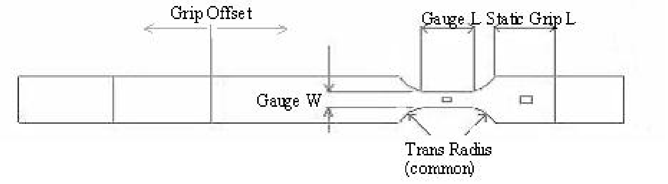

Figure 10: Definition of random geometry variables used in table.

It is desirable to investigate specimen geometry variations such as gauge length and width, transition radius and static grip length, together with boundary condition grip offset (fast jaw grip clamp position on specimen), because it may in combination with geometry affect performance measures. The geometry variations of interest are shown in figure 10, and ranges for the random input variables are listed in table 1 below. The performance measures of interest are given in the table in the results section.

Material input to the specimen model will use 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. Statistical correlation is applied to confirm geometry dependency as appropriate.

	Random variable	Nominal (mm)	Upper bound limit (mm)	Lower bound limit (mm)
Geometry	Static Grip L	40	71	40
	Trans Radius	20	36	4
	Gauge L	25	40	10
	Gauge W	10	12.5	7.5
Boundary condition	Grip Offset	0	35	-35

Table 1. Random input variables and ranges used in model.

Development of specimen designs

The Montecarlo method is used to generate one hundred unique and independent specimen designs using a uniform distribution model. Strain gauge sensor positions are maintained centred in the gauge length and static grip length. Whilst geometry is varied for each specimen, the shell 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[9]. The resulting nominal, upper and lower bound designs are shown in figure 11.

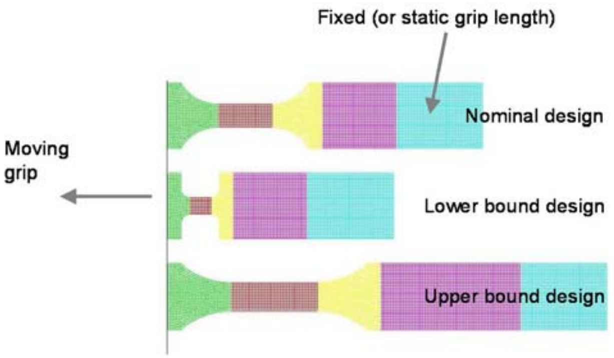

Figure 11. Models of specimen geometry variations (moving grip length to left of figure and strain gauges omitted for brevity).

RESULTS OF STOCHASTIC MODELLING

The figure 12 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. Necking development in the nominal design model is consistent with high speed camera recordings taken at 100,000 fps of an experiment at 15m/s.

Simulated results for selected performance measures from the stochastic model are shown in figure 13, and this data will be used in the analysis to follow.

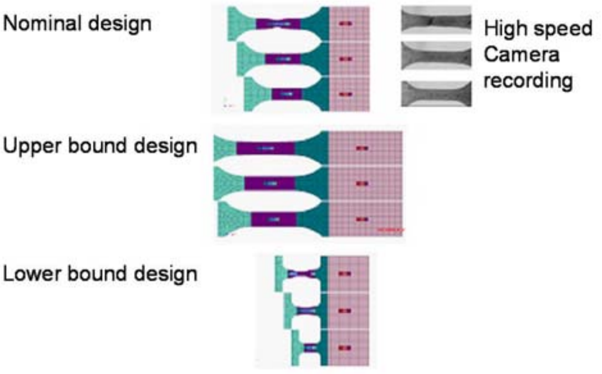

Figure 12. Verification of tensile specimen deformation modes.

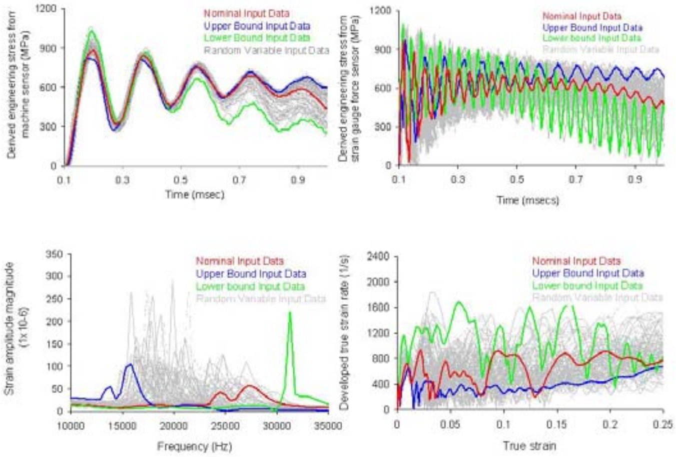

Figure 13. Upper left figure is derived engineering stress from machine force sensor versus time (bold curves are nominal bounded designs). Upper right figure is derived engineering stress from strain gauge force sensor on specimen versus time. Lower left figure is measured engineering strain from strain gauge force sensor versus time transformed to frequency domain by Fast Fourier Transform (FFT) Magnitude. Lower right figure is developed true strain rate from strain gauge strain sensor on specimen versus true strain.

PERFORMANCE MEASURES

Seven performance measures are identified for analysis and each one is listed in table 2. A short hand notation for each performance measure is assigned for future reference together with a brief description.

Notation	Performance Measure Description
Peak Strain SGFS	Peak strain at first oscillation measured from STRAIN GAUGE FORCE SENSOR on static grip length of specimen
Max Tensile Stress SGFS	Maximum tensile engineering stress derived from STRAIN GAUGE FORCE SENSOR
Max Tensile Stress MFS	Maximum tensile engineering stress derived from MACHINE FORCE SENSOR
Strain Amplitude Magnitude SGFS	Amplitude magnitude of oscillating strain derived from STRAIN GAUGE FORCE SENSOR on specimen above 10 kHz
Frequency at Strain Amplitude Magnitude SGFS	Frequency at amplitude magnitude of oscillating strain derived from STRAIN GAUGE FORCE SENSOR on specimen
Target True Strain Rate	Target true strain rate derived from approximation grip velocity divided by current gauge length averaged over true strain range 0-10%
Developed True Strain Rate SGSS	Developed true strain rate derived from STRAIN GAUGE STRAIN SENSOR on gauge length averaged over true strain range 0-10%

Table 2. Notation used to describe performance measures.

DERIVATION OF PERFORMANCE MEASURES

Peak Strain SGFS

Peak strain at first oscillation measured from strain gauge force sensor on the static grip length of specimen is established as;

$$\text{Peak Strain SGFS} = \text{Max}[e] \ [0 \text{ to } 0.1\text{msecs}]$$

Max Tensile Stress SGFS

Derived engineering stress of upper right figure 13, is computed from strain gauge force sensor on specimen, and is obtained by considering static equilibrium of forces acting between the gauge length and static grip length of specimen. The resulting expression for derived engineering stress in the gauge length is established as;

$$s = \frac{E \times e}{[\text{Gauge } W / 29]}$$

The constant of 29 mm is determined from figure 3, and e is the direct strain output from strain gauge force sensor. The expression for s is valid only if strain measurement in the static grip length in model of specimen remains elastic (i.e. below material yield). The residual load oscillation observed in upper right figure 13 is inertia in the specimen.

Maximum tensile stress is taken to mean the onset of geometric instability (or initiation of neck point) in the gauge length. To determine maximum tensile stress, it is necessary to filter the oscillations present in the derived engineering stress using the expression for s. In implementation, the resulting trend of the filtered curve appears slightly skewed from the oscillatory response at lower strain. The skew in the filtered curve is not present at intermediate and high strain, and therefore location of maximum tensile stress from the filtered curve is acceptable.

Max Tensile Stress MFS

Similarly, the expression for derived engineering stress in the gauge length computed from machine force sensor is established as;

$$s = \frac{F}{1.8 \times \text{Gauge } W}$$

The constant of 1.8 mm is the nominal thickness of specimen which is fixed for all simulations. The residual load oscillation observed in upper left figure 13 is inertia in the machine sensor and static grip head assembly.

Strain Amplitude Magnitude SGFS

The amplitude of the oscillating strain signal obtained from the strain gauge force sensor in many cases decreases until maximum tensile stress is reached, and thereafter remains constant following initiation of necking in the gauge length. Applying Fast Fourier Transformation (FFT) Magnitude to the oscillatory strain gauge force sensor versus time signal, converts it to a frequency domain. FFT Magnitude is a convenient indicator of the amount of damping present through plastic work done in the deforming specimen.

Frequency at Strain Amplitude Magnitude SGFS

The frequency at strain amplitude magnitude may be established by computing the reciprocal of the time period between any two successive oscillation peaks, as shown in upper right figure 13. The best approach is simply to identify frequency at strain amplitude magnitude from the lower left graph of figure 13.

Target True Strain Rate

Conventional strain rate[12] is established as;

$$\dot{e} = \frac{V}{Lo}$$

Conventional strain rate remains a constant, determined by the initial conditions only, and this has been referred to earlier as target strain rate. However, gauge length will extend as load is applied. The true strain rate[12] is established as;

$$\dot{\varepsilon} = \frac{d\varepsilon}{dt}$$

The equation for conventional strain rate may be modified in the denominator, by replacing the initial gauge length (Lo) by current gauge length (L) to give;

$$\dot{\varepsilon} = \frac{V}{L}$$

For a fixed grip velocity, strain rate must decrease as gauge length extends and the relationship is non-linear.

The target true strain rate will be the sum average of gauge length extensions in the range 0 to 10% true strain. However, the observed non-linearity in the range 0 to 10% true strain is so small it may be neglected. A simple definition is given as follows;

$$\dot{\varepsilon} = \frac{V}{0.5\,[Lo + L(10)]}$$

Where current gauge length $L_{(10)}$ is determined at 10% true strain. As an example, consider the nominal specimen geometry with Lo = 25 mm and V = 15000 mm/s. Conventional strain rate is determined using $^{15000}/_{25}$ and given as 600 s^{-1}. Target true strain rate is determined using $^{15000}/_{0.5[25+27.5]}$ and given as 573 s^{-1}.

Developed True Strain Rate SGSS

Developed true strain rate is the true strain output from the strain gauge strain sensor on the specimen gauge length, and differentiated with time. The true strain rate signal is however oscillatory resulting from inertia as shown in the lower right figure 13. Therefore developed true strain rate is averaged over the range 0-10% true strain.

DISCUSSION OF RESULTS

Peak Strain SGFS

The effect of gauge width on Peak Strain SGFS is shown in figure 14. Gauge width is normalised by dividing by static grip width which is fixed at 29 mm. The yield stress of the material derived from the experimental flow curve is 374.7 MPa. The dashed horizontal line of figure 14 identifies the material strain at yield assuming Young's Modulus is 210 GPa. Note the material input to stochastic model remains fixed, and there is no strain rate dependency.

In figure 14, data points above the line indicate yield strain in the static grip length of the specimen measured by the strain gauge force sensor has been exceeded. Position of current nominal design is below the line. Clearly we are not interested in those specimen geometry variations, which produce yielding in the material in a zone that must remain elastic. The cause is however of interest, and is attributed to gauge width, see figure 14. Appreciable horizontal scatter suggests other geometry influences have an affect but less significant than gauge width.

A statistical Ttest applied to the difference in means across all geometry inputs for the performance data clustered above and below the yield strain line of figure 14, identifies gauge width as the only input having an affect.

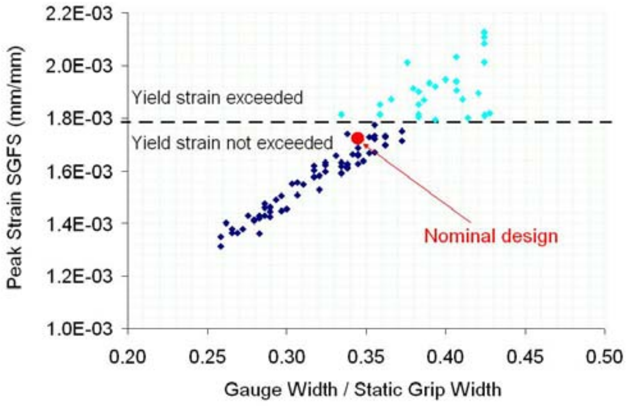

Figure 14. Geometry affect on peak strain at first oscillation derived from strain gauge force sensor.

Increasing gauge width beyond one third of the static grip width increases the likelihood of yielding in static grip length. Structural damping in the material however would attenuate the theoretical peak strain, together with friction and other losses in the load string such as between the specimen and grips. In developing a test procedure to generate reliable high strain rate test data we must however seek to minimise these losses. The recommendation is gauge width must be less than one third of the static grip width.

Max Tensile Stress SGFS

Only those specimen designs that do not exceed yield strain in the static grip length e.g. those results lying below the yield strain line of figure 14 will be considered in further analysis.

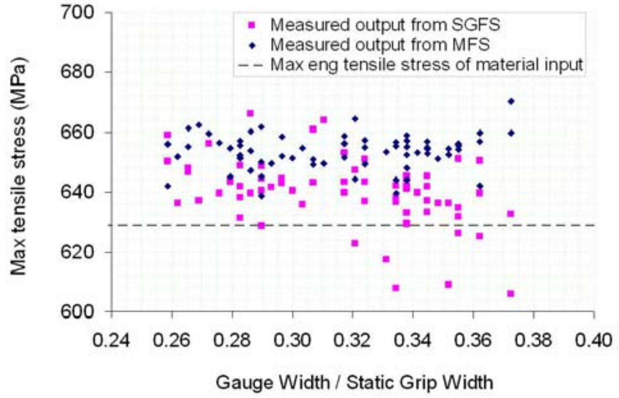

Figure 15. Geometry affect on maximum tensile engineering stress from strain gauge force sensor (SGFS) and machine force sensor (MFS).

The figure 15 shows the effect of gauge width on maximum tensile engineering stress derived from SGFS and MFS. The dashed horizontal line is the maximum tensile engineering stress of the quasi-static experimental material flow curve (629 MPa), which is input to model as true stress.

The result derived from MFS sits consistently above the horizontal line and is independent of gauge width. On the other hand the result derived from SGFS sits above the horizontal line only when ratio Gauge Width divided by Static Grip Width is below 0.31. There is a shift downward as the ratio increases beyond 0.31.

A summary of statistics from figure 15 is given in table 3 below. The coefficient of variation suggests variability in derived maximum tensile stress is low from both sensor measurements at less than 2%.

	SGFS		MFS
Range for Gauge Width / Static Grip Width	Below 0.31	Above 0.31	All
Average in range	645	633	653
One standard deviation	8.2	11.8	6.9
CoV	1.3%	1.8%	1.1%
Tvalue	11	1.8	19
Relative error	2.6%	0.7%	3.8%

Table3. Summary of statistics taken from figure 15.

The relative error between the average result from MFS and the original material input is 3.8%. The relative error between SGFS for ratio Gauge Width divided by Static Grip Width greater than 0.31 and the original material input is 0.7%. The Tvalue for ratio above 0.31 is 1.8; this is less than the two standard deviation population measure of 1.96. From which, one may state objectively, there is no significant statistical difference between Max Tensile Stress derived from SGFS for ratio above 0.31 and model input.

There appears no observable relationship between the other geometry variables and Max Tensile Stress derived from both machine force sensor and strain gauge force sensor.

A general recommendation is Gauge Width divided by Static Grip Width ratio is greater than 0.31.

Strain Amplitude Magnitude SGFS

The amplitude magnitude of the oscillating strain signal derived from the strain gauge force sensor has three geometry dependencies; these are gauge length, static grip length, and transition radius, see figure 16 and 17.

In figure 16, the result shows it is necessary to reduce static grip length and increase gauge length to maximise the rate of attenuation of amplitude of load oscillation during uniform elongation of gauge length.

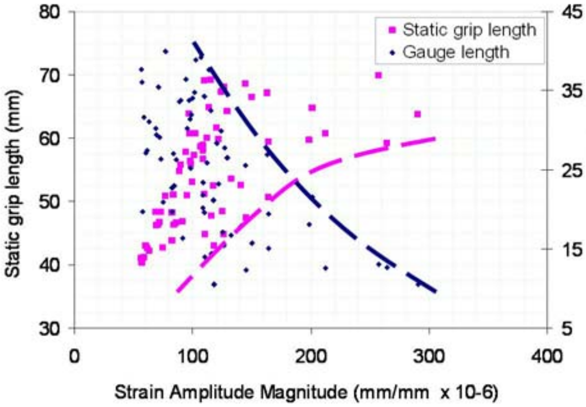

Figure 16. Geometry affect on amplitude of load oscillation derived from strain gauge force sensor.

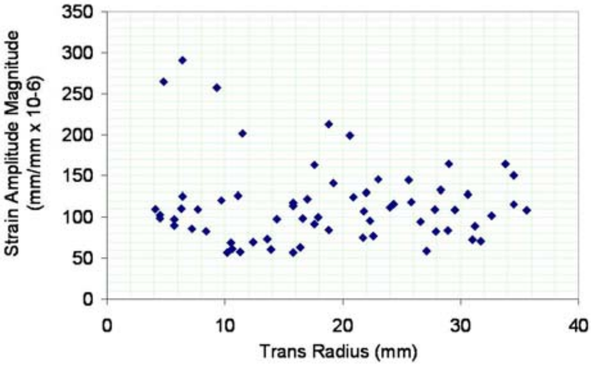

Figure 17. Effect of transition radius on amplitude of load oscillation derived from strain gauge force sensor.

The figure 17 suggests a more complicated relationship exists between transition radius and amplitude of the oscillating strain signal that develops. In generalising one could conclude that a smaller transition radius increases the likelihood of sustained amplitude of load oscillation during uniform elongation of gauge length, and therefore it is better to increase transition radius in the design range tested. On the other hand a cluster of results with low strain amplitude magnitude is observed in the transition radius range 12 to 16 mm. Below 10 mm transition radius, strain amplitude magnitude appears to increase for all results.

In making a general recommendation for transition radius, it is suggested a transition radius above 12 mm is desirable, if the objective is to maximise the rate of attenuation of amplitude of load oscillation during uniform elongation of gauge length. However, a transition radius between 12 and 14 mm appears attractive.

Frequency at Strain Amplitude Magnitude SGFS

Frequency at strain amplitude magnitude of oscillating strain signal from strain gauge force sensor has geometry dependency static grip length, which is seen to be non-linear in figure 18. The sensitivity of this performance measure to static grip length is increased, as static grip length is reduced because the slope is increasing.

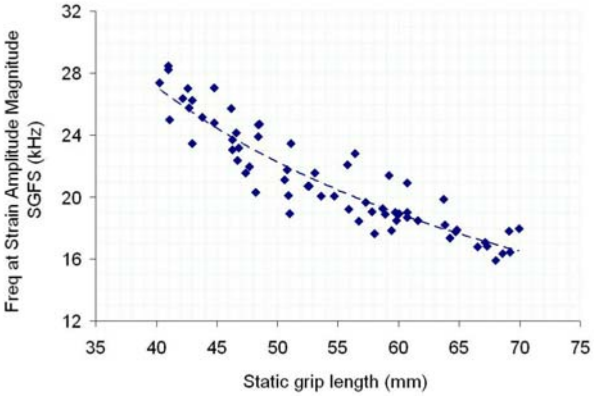

Figure 18. Effect on static grip length on frequency of load oscillation derived from strain gauge force sensor.

The first natural frequency of static grip length is proportional to the reciprocal of static grip length. Replacing the abscissa in figure 18 with the first natural frequency of static grip length returns a linear relationship. Hence frequency at strain amplitude magnitude is linearly proportional to the reciprocal of static grip length in the design range tested.

To increase the frequency response of the strain gauge force sensor measurement it is recommended to minimise static grip length.

True Strain Rate

The figure 19 shows target true strain rate has linear dependency on the first natural frequency of gauge length.

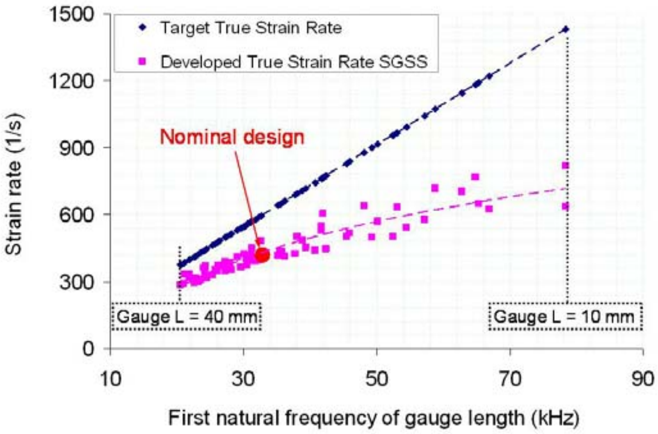

Figure 19. Effect of gauge length on strain rate from strain gauge strain sensor on gauge length

First natural frequency is in turn, proportional to the reciprocal of gauge length. Therefore, it follows that target strain rate has geometry dependency on gauge length. There is also a well defined relationship between developed true strain rate derived from strain gauge strain sensor on gauge length and first natural frequency of gauge length, which is non-linear.

By increasing the first natural frequency (or reducing gauge length), the relative error between target and developed true strain rate increases typically from 15% at 40 mm to near 100% at 10 mm.

A general recommendation is to increase gauge length in the design range tested to minimise the difference between target and developed true strain rate.

Boundary Condition – Grip Offset

A discernable relationship between boundary condition grip offset on specimen moving grip length and each performance measure could not be identified in the design range tested. On this basis it could be concluded that grip offset has minimal influence on the performance measures considered in this study.

SUMMARY OF RECOMMENDATIONS

Arising from this study the following recommendations are proposed to develop an improved tensile specimen design for high strength sheet steel, and hence test procedure, suitable for generation of strain rate sensitivity data on a high speed servo-hydraulic machine;

- Minimise static grip length in the design range tested (40 to 71 mm)
- Maximise gauge length in the design range tested (10 to 40 mm)
- Ratio of gauge width to static grip width must be smaller than 0.33 and ideally greater than 0.31
- Transition radius greater than 12 mm, an optimum could be between 12 and 14 mm

These recommendations apply to a specimen design, suitably instrumented with strain gauges, to measure force in the static grip length and strain in the gauge length.

On implementing these recommendations and using maximum tensile stress as a metric, the test procedure is capable of generating strain rate sensitivity data with a theoretical error of less than 1%.

In developing a high speed tensile specimen design, it is important to take into consideration other constraints on specimen design such as the ratio gauge length to gauge width, to ensure consistency in deriving tensile data across the strain rate range of interest for crash design ~ quasi-static to $600s^{-1}$.

Finally, the recommendations proposed for specimen design do not excuse the careful preparations required for the manufacture of high speed tensile specimens, strain gauging, and specimen alignment in test machine. In addition it is important to monitor wear on jaw faces, which is accelerated through testing harder materials.

CONCLUSION

The gauge length of the high speed tensile specimen is a key design parameter. For a fixed grip velocity, which is very often dictated by the capability of the servo-hydraulic test machine, the gauge length is varied to deliver the desired strain rate. The results of the stochastic model have shown that the developed true strain rate deviates further from the target or expected true strain rate as gauge length is reduced from 40 mm to 10 mm, as such delivering an increasingly lower than expected strain rate; this deviation is consistent with the results derived from practical experiments.

Increasing gauge length, gives more opportunity for strain rate oscillation measured from the strain gauge strain sensor to decay, within the range of uniform plastic elongation.

Increasing gauge length in combination with tuning the other design parameters, such as static grip length, transition radius, and gauge width following the proposed recommendations, will enable an increased frequency response measured from the strain gauge force sensor, together with an increased rate of attenuation of load oscillation.

Implementing the detailed recommendations proposed in this paper is expected to improve the accuracy and precision, in dynamic tensile mechanical property measurements of high strength sheet steels at high strain rates. They also compliment those more general recommendations which have been published within the last year[5][7] and another, which is still in draft[8].

FORWARD PLAN

To conduct a number of experiments to verify the results from the model, for an improved specimen design and hence test procedure.

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REFERENCES

1. Cornette D., T. Hourman, O. Hudin, J.P.Laurent, A. Reynaert, High Strength Steels for Automotive Safety Parts, SAE Technical Paper Series, 2001-01-0078

2.http://www.worldautosteel.org/pdf_hsrt/RptRndRobResults.pdf
3. BS EN 10002-1:2001 (low speed tensile testing of metallic materials and mechanical property characterisation)
4. VHS 160/100-20 High Strain Rate Test System and Accessories, Instron Ltd, Coronation Rd, High Wycombe, Bucks, England
5. International Iron and Steel Institute (IISI) – High Strain Rate Experts Group. Recommendations for Dynamic Tensile Testing of Sheet Steels, pub August 2005.
6. Hoffmann K., An Introduction to Measurements using Strain Gauges, pub 1989, Hottinger Baldwin Messtechnik GmbH, Darmstadt.
7. Yan B. Y. Kuriyama, A. Uenishi, D. Cornette, M. Borsutzki, C. Wong. Recommended Practice for Dynamic Testing of Sheet Steels – Development and Round Robin Tests. SAE International 2006.
8. STAHL-EISEN-Prüfblätter (SEP) des Stahlinstituts VDEh, The Determination of the Mechanical Properties of Sheet Metal at High Strain Rates in High-Speed Tensile Tests, SEP 1230, 1st Ed., April 2006.
9. Ove Arup and Partners, Oasys LS-DYNA, The Arup Campus, Blythe Valley Park, Solihull, B90 8AE, UK.
10. Wood P.K.C. and C.A. Schley. Material Data Management Tool – Models and Processes to Transform Raw Material Data for Input to CAE Tools (proprietary software), Flat 41, Brindley Point, 20 Sheepcote Street, Birmingham, B16 8AE
11. Wood P.K.C., et. al. Characterising Performance of Automotive Materials at High Strain Rate for Improved Crash Design. 6th Int. Conf. on Materials for Lean Weight Vehicles 7-8th Dec. 2005.
12. Dieter G. E., Mechanical Metallurgy, McGraw-Hill, 1988, ISBN 0-07-100406-8

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

IARC: International Automotive Research Centre

DAQ: Data Acquisition

F: Output from dynamically calibrated machine force sensor

s: Derived engineering stress

σ: Derived true stress

e: Derived engineering strain computed from strain gauge sensor

ε: Derived true strain computed from strain gauge sensor

$\dot{e}$: Conventional strain rate

$\dot{\varepsilon}$: True strain rate

E: Young's Modulus of steel taken as 210 GPa

Lo: Original length of strain gauge sensor measuring grid or gauge length

L: Current length of strain gauge sensor measuring grid or gauge length

t: time

V: Grip velocity

CoV: Coefficient of variation (%) = one standard deviation divided by average in range

Tvalue: Difference based on a sample estimate at 5% risk with 30 degrees of freedom

Relative error: (actual value-correct value)/correct value