STUDIES TOWARD OPTIMUM INSTRUMENTED STRIKER DESIGNS

M. P. Manahan, Sr.[1] and R. B. Stonesifer[2]

[1] President MPM Technologies, Inc., 2161 Sandy Drive, State College, PA 16803
[2] President Computational Mechanics, Inc., 1430 Steele Hollow Road, Julian, PA 16844

ABSTRACT

Experimental and numerical studies have shown that the accuracy of indicated loads from instrumented Charpy impact test strikers may be adversely affected by inertial forces in the striker and by variations in the contact force distribution between the striker and the specimen. This study identifies the factors that affect contact force distribution on the striker and discusses how they can adversely affect the load cell's calibration and use during dynamic testing. Results of numerical simulations are presented which show that inertial errors increase significantly as strain gages are moved farther from the contact surface and that significant errors for high frequency components of the load signal may be experienced for some designs. Numerical and experimental studies show that load cell designs can be made significantly less sensitive to the load distribution variations that occur in a Charpy V-notch test by optimizing the strain gage locations. Experimental data are provided which demonstrate that proper design and calibration can adequately address inertial and load distribution effects and result in acceptable errors in the dynamic loads.

KEYWORDS: Charpy, instrumented impact test, absorbed energy, encoder, calibration.

INTRODUCTION

Charpy impact testing has been in use for over 100 years and remains a key means for fracture toughness testing due to its low cost and reliability. Through continued refinements in testing and certification standards, the Charpy test has evolved with the requirements of the engineering community. Due to its low cost and convenience, there is a growing interest in using the test to obtain more sophisticated fracture mechanics related material information (e.g., K_{Ic}, K_{Ia}). Accurate determination of load versus displacement behavior during the test is essential to obtaining such information. The most common way for determining the transient load history during a Charpy test is to place strain gages on the striker so that the striker becomes a load cell. Displacements are typically obtained by integrating the acceleration versus time record twice with respect to time. It can be seen that the accurate determination of any material fracture properties from these load measurements will depend very significantly on the accuracy of the striker load cell.

FORCE DISTRIBUTION EFFECTS

Building a load cell into the striker of a dynamic test machine requires solution to two fundamental problems. The first is that the measured loads must be accurate for very high rates of loading since the rapidly changing loads (initial loading, brittle fracture unloading) being measured are typically applied and removed over a microsecond time scale. At these rates of loading, the striker material's inertial forces are not entirely negligible in comparison to the contact forces between the specimen and the striker. The other problem is that the striker geometry is not inherently ideal for use as a precision load cell. The principal problem is that the measured strains for a given load magnitude are dependent on the manner in which the load is distributed over the specimen/striker contact region. Some results of finite element simulations related to load distribution effects on striker accuracy were reported in a previous study [1]. Additional finite element simulations and experimentation toward minimizing inertial and contact force distribution effects on load cell accuracy are presented here.

For a standard Charpy V-notch test, there are numerous reasons why the contact force distribution can vary from specimen-to-specimen or during a test on a single specimen. The most significant reasons (in no particular order) are listed below:

1. elastic deformations of the striker and pendulum
2. rotations of the striker due to pendulum rigid body rotation
3. initial specimen machining tolerance on squareness (10 minutes)
4. wear of the striker, anvils, or supports
5. plasticity in the specimen leading to force redistribution
6. wrapping of the specimen around an 8 mm striker with plowing of the specimen surface and associated pinching of the striker nose
7. specimens of different material elastic and plastic behavior
8. specimen height
9. nonsymmetry in crack growth behavior

The effects of force distributions on the striker can be grouped according to whether the distribution is defined with respect to a vertical coordinate (i.e., parallel to the specimen's notch root when placed in the testing machine), or a horizontal coordinate (perpendicular to the intended fracture plane of the specimen). In our previous work, simulations of bounding horizontal load distribution variations on an 8 mm striker (nominal 4 mm wide contact surface with an 8 mm radius) striker showed a maximum load cell error of 1.2%. The considered contact force distributions were a) uniform pressure, b) vertical line of force at the centerline of the striker, and c) two vertical lines of force at the corners of the 4 mm wide contact surface. The simulated strain gage placement was 7.4 mm from the contact surface. Recent simulations with a 7.9 mm gage placement predicted a 1.0% maximum load cell error for these same distributions.

Kalthoff et al [2] experimented with load distribution effects on 2 mm and 8 mm strikers. Their study focused on horizontal load distribution effects by considering the effect that wrapping around the striker at large specimen deformation levels could have on load cell accuracy. They found load cell errors as large as 10%, with titanium strikers being more prone to error than steel, and the 8 mm design being more prone to error than the 2 mm design. The 8 mm striker results of the current horizontal load distributions study are consistent with the Reference [2] experimental results of ±1 to 2% error (steel striker with strain gages on the sides of the striker).

Simulations of vertical load distribution variations on an 8 mm striker showed a much larger potential for load cell error than variations in horizontal distributions. Bounding distributions (which are never realized in actual tests) where all load was concentrated at either the top or the bottom specimen edge led to large load cell differences when the load cell output is compared with a uniform contact pressure. Although the range of realistic contact distributions are not known, this earlier study suggested that errors on the order of 8% might be expected. This level of error is consistent with those reported by Kobayashi et al [3]. They discuss the effect of specimen thickness and specimen elastic modulus on a 2 mm radius striker load cell calibration. Their finite element simulations show that load errors on the order of 10% can be expected if a test is done on an aluminum specimen after calibration using a steel specimen. They also found that calibrating with a 10 mm thick specimen and then testing a 2 mm thick specimen could lead to load errors on the order of 10%. Although they do not clearly state that the load cell errors are due to changes in load distribution on the striker, this is clearly the explanation for their observations. They reasonably conclude that an instrumented striker system must be calibrated for any new specimen material or specimen size. They do not broach the subject of changing contact force distributions that can occur within a single test due to plasticity or striker rotation. Winkler and Voβ [4] report experiments that show a maximum 5% error in an 8 mm style striker due to variations in load distribution. The variations they considered were those due to wear or small permanent deformations in the calibration specimen and/or striker that led to different contact force distributions and different calibration factors with subsequent calibrations and with different calibration force levels.

The Manahan and Stonesifer study [1] on striker load cell sensitivity to load distribution showed that the elastic contact surface rotation for an 8 mm striker on a U-hammer machine is similar in magnitude to the allowable 10 minute squareness requirement of the ASTM E23 standard, thus making the 10 minute squareness tolerance seem reasonable. Very high energy Charpy specimens can be in contact with the striker while the pendulum rotates as much as 1 to 2 degrees. At the 2 degree angle of rotation, a typical 400 J machine will have displaced the bottom edge of the specimen by about 0.35 mm more than the top edge. This top-to-bottom nonsymmetry provides significant opportunity for a larger portion of the applied load being applied to the bottom half of the specimen during a significant portion of the test duration. It seems likely that the nonsymmetry would be greatest after peak load since the increasing loads and associated plasticity prior to peak load would be more effective at preserving top-to-bottom symmetry in the contact force distribution.

Finite element simulation showed that the contact forces between an 8 mm striker (U-hammer) and a Charpy specimen under linear elastic conditions are not uniformly distributed. The distribution will have peaks at the top and bottom edges of the contact region with the top peak being larger in magnitude than the bottom peak. The peaks are due to the corners of the specimen pressing into the striker surface. The top-to-bottom asymmetry results from the striker being connected to the hammer only at its top edge and is made even more significant by the specimen contact region being relatively close to the free bottom edge of the striker. The tendency for larger contact forces at the specimen's top edge is significant. The ratio of the top and bottom edge node forces was 1.21. A statically equivalent linear pressure distribution has a top-to-bottom ratio of 1.25. Examination of broken Charpy V-notch specimens that have undergone significant plasticity prior to fracture shows clear signs of the contact forces tending to concentrate near the middle of the specimen's contacting surface. The mid region concentration is due to a tendency for the mid region to bulge relative to the top and bottom edges during large fully plastic bending deformations at the notched plane. The initial elastic distribution for a specimen is probably a good approximation to the distribution during calibration if the calibration specimen is not worn from previous calibrations [4]. However, the distribution of force during later stages of deformation of a ductile specimen will probably never be reasonably approximated by calibration on a typical calibration specimen. If the load cell is to accurately measure the load for both distributions, it must either be generally insensitive to changes in load distribution or it must be designed to be accurate for at least the specific load distributions that occur during calibration and testing.

The described numerical and experimental studies clearly show that significant errors in the indicated load from a striker load cell can occur if the load during the test is not distributed on the striker surface in a manner similar to that experienced during calibration. This sensitivity to contact force distribution is an illustration of Saint-Venant's principle. Basically, application of this principle leads to the conclusion that if one hopes to measure strains that are insensitive to load distribution, the strain gages must be relatively far from the loaded surface relative to the dimensions of the contact region. Unfortunately, it is not feasible to design a striker load cell that makes use of this principle to minimize load distribution sensitivity. Even if the striker was large enough to accommodate such distances, the sensitivity of the load cell to the magnitude of the load would suffer significantly. However, an even more limiting factor is the effect of this distance on the load cell's dynamic response.

INERTIA EFFECTS

Consideration of inertial effects is important because the accuracy of loads measured during high frequency events (e.g. brittle fracture events) can be significantly affected for inferior striker designs. The inertia of the material between the contact surface and the strain gage affects the ability of a statically calibrated load cell to faithfully reproduce the shape and magnitude of load versus time impulses applied at the contact surface. As the strain gages are moved closer to the contact surface, the inertial effects become smaller due to the reduced intervening mass. Comparing the results for the two simulated strain gage positions (3.3 mm and 7.4 mm from the contact surface), it can be seen that the closer gages follow the applied force versus time curve more faithfully than the farther gages. It has also been verified by comparing results for 25 and 50 kHz inputs that the "inertial errors" (i.e., difference from the applied force behavior) increase as the duration of the pulse is decreased (i.e., higher frequency). The non-zero indicated forces after the applied force is zero are associated with audible "ringing" of the striker (from stress waves that continue to bounce from surface to surface within the striker). For an impulse duration of 100 microseconds (5 kHz case), the peak load error is less than 1% for both simulated gage locations and the maximum inertial errors are 3.6% and 5.5% for the 3.3 and 7.4 mm position, respectively. This pulse duration is similar to the duration of A533B Class 1 steel tested on the lower shelf and therefore it might be expected to be representative of typical inertia related load cell errors for such a test. However, the load oscillations that typically occur until damped by specimen plasticity have a frequency of around 20 kHz. If the amplitude of this oscillatory load is say 20% of the peak load then, the larger inertial errors associated with this 20 kHz component can effectively about double the magnitude of the indicated load error suggested by the 5 kHz input case.

The importance of the errors at these higher frequencies depends on the high frequency content of the load signals of interest. One could do a Fourier analysis of typical load signals and then estimate errors based on the amplitudes of the various frequencies. However, a more direct and probably more reliable approach is to input actual force versus time records from a variety of Charpy tests and compare the input and indicated loads. Finite element simulations of an actual lower shelf 4340 steel test specimen record using a simulated load cell with gages 7.9 mm from the contact surface led to load errors near peak load of 2 to 4% and load errors near the crack arrest load of 5 to 14%. This simulation confirmed the importance of the higher frequency load components in the overall accuracy of the indicated load. Simulations of an upper transition region specimen led to load errors near peak load of 0.5% to 2% and load errors near the arrest load (arrest load being ~2/3 peak load) of 1 to 3%. The smaller errors near peak load were due to damping of high frequency oscillations by specimen plasticity and were expected. The smaller errors near the rapid crack extension event (compared to the low energy simulation) were not expected.

OPTIMUM STRIKER LOAD CELL DESIGN

The striker load cell FEM simulations led to the conclusion that while the 3.3 mm gage location was better in terms of reducing inertial effects, it was too sensitive to load distribution effects. Based on the significant inertial errors (primarily for crack arrest load measurement) for 25 kHz and higher frequencies at the 7.4 mm gage location, it was concluded that placing gages significantly farther than 7.4 mm from the contact surface would make the load cell too sensitive to inertial effects. Having established that gages that are about 7.4 mm from the loaded surface seem to provide a reasonable balance between load distribution related errors and inertia related errors, an experimental study was conducted to refine the gage placement in an attempt to minimize sensitivity to load distribution effects. Since the distance from the contact surface was being confined to values close to 7.4 mm, the only other geometric parameter to be determined was the vertical position of the gage relative to the center of the nominal striker contact region. In preparation for the optimization process, strain distributions and simulated load cell outputs were computed for a variety of assumed vertical distributions of contact force. A very significant finding was that for a selected pair of contact force distributions, a vertical gage position could be identified for which the simulated load cell outputs would exactly reproduce the input force magnitudes for both selected load distributions. It was also found that some vertical gage locations tended to give smaller indicated load errors for a range of assumed distributions. By assuming which contact distributions were of key importance, the finite element results could provide the associated optimum gage position.

Table 1 Example of measured load variation at or near peak load for four strain gage locations.

	Striker Strain Gage Location			
Material	**FEM Calculation (below optimal location)**	**Strain Gage Position 2 (above optimal location)**	**Strain Gage Position 3 Near Optimum Location**	**Optimum Location**
4340 Steel	-4.28 %	5.45 %	-1.06 %	0.09 %
17-4-H1150	-5.28 %	8.54 %	-1.70 %	-0.15 %
A36 Steel	-3.95 %	3.07 %	-1.75 %	-0.13 %
6061 Aluminum	-5.34 %	-3.63 %	-1.66 %	-0.06 %
17-4 PH condition A	-5.17 %	7.92 %	-0.78 %	-0.20 %

NOTE: Calculation of the variation was performed at peak load for cases where the deflection was less than 2.5 mm or at 2.5 mm of deflection.

In order to test the candidate strain gage locations, static load deflection measurements on standard Charpy specimens were made using the Charpy test machine striker and a NIST traceable calibrated load cell. The striker load cell was calibrated using a hardened, reusable calibration specimen. After calibration, slow bend tests were performed using conventional Charpy V-notch specimens fabricated from a variety of steels and aluminum. The results of the experimental gage placement optimization are summarized in Table 1 for peak load measurements. The load application fixture was not designed for deflections in excess of about

2.5 mm. Therefore, the loads in Table 1 are at peak load for cases where the deflection was less than 2.5 mm or at 2.5 mm of deflection. It was found that the FEM calculated optimum gage position (based on assumed key load distributions) resulted in the striker's indicated load being about 5% lower than the applied load. A second bounding location was chosen for the gages which yielded striker indicated loads that were generally above the applied load. These data suggested that a better gage position existed and that it was between the first two locations. Using these data, a new estimate of the optimum gage location was made and further experimentation was performed to verify it. As shown in Table 1, this third gage location gave peak loads accurate to within 2% of the applied load for the variety of steels and aluminum. Again using the existing data a fourth gage location was identified and tested. For this fourth location, the peak load errors were all 0.2% or less and therefore this position was declared the optimum gage location.

The experimental vertical position refinement resulted in about a 46% change to the initial finite element based vertical gage offset. This suggested that the force distributions used in the numerical optimization step were not the best choices. The experimental refinement of the numerical optimum location provided sufficient information to determine how the selected load distributions would need to be modified to bring the analysis and experimental results into agreement. To have the numerical optimization match the experimental optimum gage location required more load to be applied on the bottom half of the specimen than on the top half for the second of the two assumed load distributions. This is the opposite gradient from the initial contact distribution.

DESIGN OPTIMIZATION VERIFICATION

An experiment was designed to verify the accuracy of the optimized striker design. After construction of the striker, a static striker calibration was performed using a stiff, hardened, reusable calibrator specimen. After this calibration, the same calibration fixture was used to perform static load-deflection experiments using conventional Charpy specimens. These tests allowed the effects of changes in specimen stiffness, specimen material, and large specimen deflections on contact load distribution and load cell response to be studied. Fig. 1 shows the static load calibration results for several materials with widely differing properties and load-deflection responses. It can be seen that the striker's indicated loads are in excellent agreement with the applied loads. Therefore, it has been concluded that the striker design is not significantly affected by the type of load distribution changes that are experienced in going from a calibration specimen to a real Charpy specimen or the changes that can occur during testing of Charpy specimens.

As discussed earlier, load cell inertial effects on the crack arrest load measurement is a concern. Fig. 2 shows a load-time plot for a pressure vessel steel tested in the transition region. In cases where the brittle pop occurs after peak load, the specimen plasticity has damped the load oscillations and the brittle initiation load is expected to have no significant inertial effects. However, the brittle fracture and arrest events occur on a microsecond time scale and therefore load cell inertial effects on the indicated loads near the time of crack arrest are probably significant. As shown in Fig. 2, backward extrapolation of a fit to the post-brittle fracture load data appears to provide a reasonably well defined crack arrest load that should be relatively insensitive to load cell inertial effects. Since it seems likely that actual specimen load oscillations during this time may never be accurately separated from load cell inertial effects, it may be more meaningful and reliable for fracture mechanics analyses involving the crack arrest load to use the quasi-static fitting procedure to define the crack arrest load.

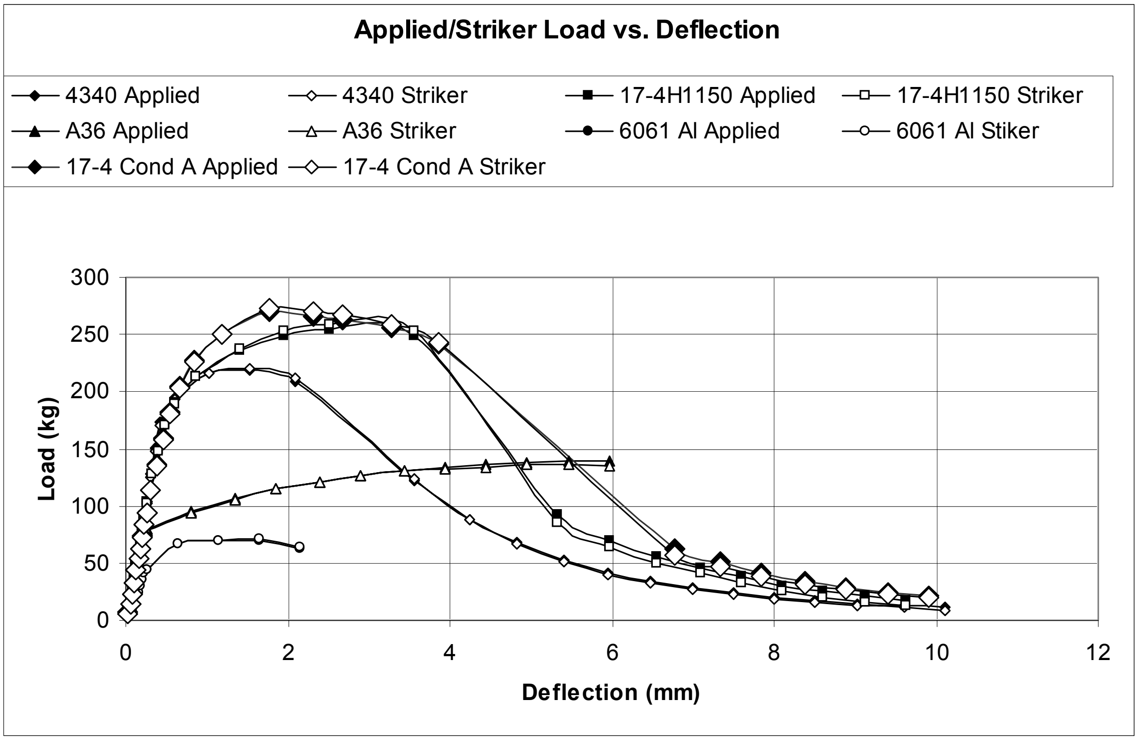

Fig. 1 Static load calibration results for five materials with various load-deflection responses. The load application device was designed to provide accurate data up to deflections of about 2.5 mm. Therefore, data at deflections above 2.5 mm should be viewed as approximate.

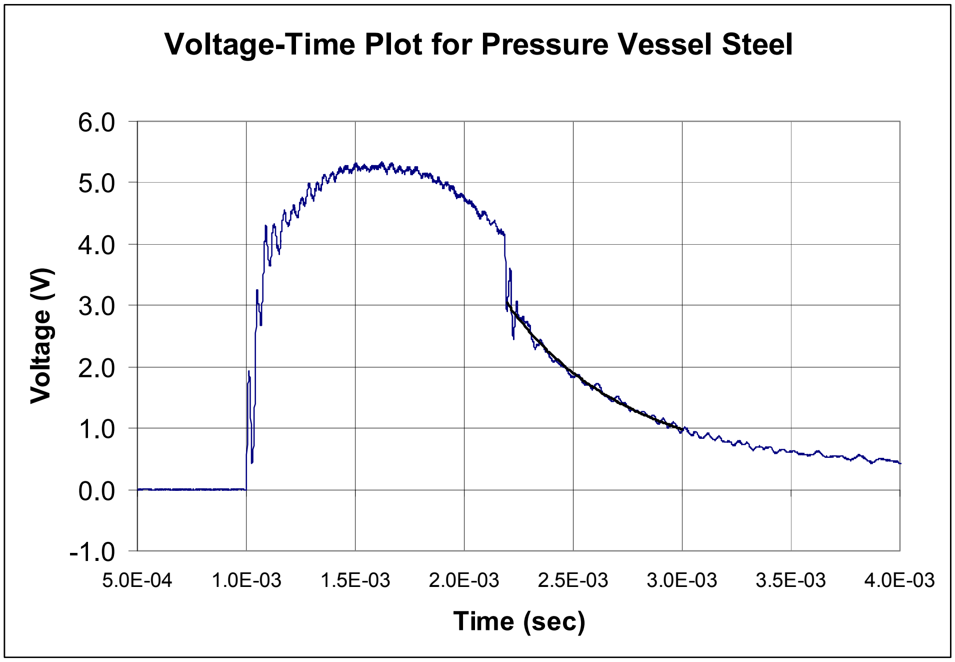

Fig. 2 Instrumented striker signal showing rapid unloading due to brittle crack propagation. Fitting of quasi-static post-brittle fracture data shows that the measured crack arrest load is well represented by the quasi-static load.

SUMMARY AND CONCLUSION

It has become apparent through a variety of experimental and numerical studies that the accuracy of indicated loads from instrumented Charpy impact test strikers are adversely affected by inertial forces in the striker and by variations in the contact force distribution between the striker and the specimen. Numerical and experimental evidence shows that the vertical distribution of striker contact force changes significantly during a typical Charpy test.

Inertial force effects on the load cell can be reduced by moving the load cell strain gages closer to the contact surface. Contact force distribution effects can be reduced by moving the load cell strain gages farther from the contact surface. A distance of 7 to 8 mm was found to provide a reasonable compromise between inertial and load distribution effects. It was shown that sensitivity of the load cell to variations in the contact force distribution (between calibration and testing and during a given test) is significantly improved by optimizing the vertical location of the load cell strain gages relative to the contact surface.

REFERENCES

1. Manahan, M. P., Sr., and Stonesifer, R. B., **"The Difference Between Total Absorbed Energy Measured Using An Instrumented Striker and That Obtained Using an Optical Encoder,"** *Pendulum Impact Testing: A Century of Progress, STP 1380*, T. A. Siewert and M. P. Manahan, Sr., Eds., American Society for Testing and Materials, West Conshohocken, PA.
2. Kalthoff, J. F., van Walle, E., and Wilde, G., **Variations of the sensitivity of instrumented ISO/DIN and ASTM tups and their influence on the determination of impact energies in tests with ductile steels**, *Evaluating Material Properties by Dynamic Testing*, ESIS 20 (Edited by E. van Walle), 1996, Mechanical Engineering Publications, London, pp. 25-35.
3. Kobayashi, T., Inoue, N., Morita, S., and Toda, H., **"On the Accuracy of Measurement and Calibration of Load Signal in the Instrumented Charpy Impact Test,"** *Pendulum Impact Testing: A Century of Progress, STP 1380*, T. A. Siewert and M. P. Manahan, Sr., Eds., American Society for Testing and Materials, West Conshohocken, PA.
4. Winkler, S. and Voβ, B., **Static force calibration of Charpy impactors**, *Evaluating Material Properties by Dynamic Testing*, ESIS 20 (Edited by E. van Walle), 1996, Mechanical Engineering Publications, London, pp. 37-44.