

Results of Auto/Steel Partnership (A/SP) Steel Tube Hydroforming Materials and Lubricants Experimental Projects

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ABSTRACT

Over the past twelve years the Auto/Steel Partnership (A/SP) Tube Hydroforming Materials and Lubricants Team has been conducting projects to aid the implementation of tubular hydroforming in automotive applications. The approach taken has been to initially gain a basic understanding of the hydroforming process and potential issues and to then extend learning to real world applications of increasing complexity.

The experimental project investigations have encompassed various steel grades with a recent focus on advanced high strength steel (AHSS) and tailor welded tubes (TWTs) in free expansion and corner fill processes using several types of lubricants.

Project plans are developed based on identified knowledge gaps, barriers to implementation and technology needs as follows:

- Effects of forming operations prior to hydroforming including tube making, pre-bending and pre-forming.
- Forming limits (e.g. forming limit diagrams (FLDs)) and other failure criterion.
- Experience with AHSS in hydroforming applications is limited.
- Attitude is conservative toward new materials and envelope-pushing applications.
- Need to demonstrate the benefits of tube hydroforming through projects focused on real world applications
- Limited computer modeling knowledge and lack of validated tools for automotive design process.

This paper will review a few of the projects that have been conducted by the A/SP Hydroforming Materials

and Lubricants Team as well as present results and major findings of these projects. The entire database of experimental results and learning is available for use by other researchers to support implementation of steel tube hydroform automotive solutions and for validation of computer models through A/SP (www.a-sp.org).

INTRODUCTION

BACKGROUND - The use of tubular hydroforming technology in automotive applications has been increasing due to the inherent advantages of improved dimensional accuracy, increased stiffness in bending and torsion modes, and the ability to consolidate several parts into one part. These advantages allow design engineers to reduce both the cost and the weight of automotive structures provided they have sufficient knowledge on manufacturability to be able to fully exploit the advantages of the tubular hydroforming process. (1)

Presently, the formability limits for steel in a tubular hydroforming process are poorly understood and practitioners commonly use the sheet steel forming limits developed for conventional stamping processes. Also, the effect of the prior strain induced in tube manufacturing, tube bending and pre-forming that precede the hydroforming operation have been ignored. Accuracy needs to be assessed and improved to allow optimum application in the lightweighting of vehicles.

Additionally, the tests that tube producers are using to evaluate tube quality do not properly address metal forming issues relevant to tubular hydroforming. The current tests focus on weld quality and dimensional accuracy of the tubes but do not adequately describe the amount of ductility left in the tube for post-forming operations, such as hydroforming. There is a need to develop and evaluate tube testing methods that are suitable for evaluating and comparing material formability and are also suitable for input into finite element models.

Furthermore, more information is needed on the fundamental material attributes that control the hydroformability limits of steel. This knowledge will allow steelmakers to develop appropriate new steel grades or appropriately apply existing steel grades to hydroforming applications.

OBJECTIVE - The ultimate goal of the A/SP Hydroforming Materials and Lubricants Team is to identify and overcome the design, manufacturing and material barriers for the use of sheet steel from mild to advanced high strength steel (AHSS) when applied to automotive tubular hydroforming applications. This will be accomplished by conducting projects aimed at achieving the following objectives:

- Develop mechanical test procedures and forming limit diagrams (FLDs) for tubes.
- Improve the accuracy and confidence in finite element modeling (FEM) of tubular hydroforming.
- Investigate the fabricating and performance characteristics of tailor welded tubes (TWTs).
- Expand understanding of steel and lubricant requirements for hydroforming using a combination of experiments and FEM.
- Establish awareness of the structural and cost benefits of hydroformed components.
- Support the work of other A/SP project teams when hydroformed structural components are investigated.
- Validate the performance benefits of hydroforming in automotive structures.
- Facilitate the adoption of cutting-edge hydroforming applications (AHSS TWTs) in vehicle structures.

DESCRIPTION OF TUBE HYDROFORMING - The hydroform process involves the conversion of a tube into a component of variable cross section by forming with internal fluid pressure in a closed die set. Pressure level is dictated by material and part geometry and can be as high as 25,000 psi (170 MPa) and higher. Prior to hydroforming, tube bending and/or tube crushing may be required to obtain the general part shape. During hydroforming, end feeding of the tube into the die cavity may be employed.

Pressure sequence hydroforming (PSH) is a subset of tube hydroforming. PSH utilizes the fluid as a mandrel to re-shape the tube. Since circumferential expansion is not possible with PSH, it has significant design limitations compared to conventional hydroforming. Dimensional repeatability of conventional hydroforming is expected to be better than PSH although both processes have much less variability than stamping.

APPLICATIONS - Tube hydroforming is a candidate technology for any closed section part. The greatest application is in vehicle chassis components. Examples include the front subframe (i.e. engine cradle) for unibody (monocoque) and frames for body-on-frame vehicles. Applications also exist outside of the automotive sector. For example, plumbing fixtures (an early application was the production of copper plumbing tees), appliance and bicycle frame components, motorcycle parts and furniture and lighting fixtures are today manufactured by tubular hydroforming.

Automotive body-in-white (BIW) applications (i.e., door pillars, rockers, etc.), whether for unibody or body-on-frame, are growing slower and are expected to plateau at a much lower level of penetration. Difficulties joining sheet metal stampings to tubes which lack flanges, large changes in cross section geometry on parts like pillars and assembly plant unfamiliarity with integrating and joining tube hydroform components into the BIW are some of the impediments. For example, assembly plants are comfortable with spot welding, not 3D laser welding which may be necessary for joining products

components. (1) A joint A/SP and United States Council for Automotive Research (USCAR) project is currently examining thermal drilling for HSS hydroformed part joining to overcome this issue.

A/SP HYDROFORM PROJECTS - The A/SP Hydroforming Materials and Lubricants (herein referred to as A/SP Hydroform) Team began about 12 years ago and has conducted numerous projects to achieve its objectives. Projects have been contracted to companies and research institutions with expertise in the areas of study. Many of the fundamental hydroforming projects were contracted to the Industrial Research and Development Institute (IRDI) in Midland, Ontario.

One of the early projects was a demonstration project using small scale simulation parts at a production hydroforming company. This study revealed the need to first establish fundamental understanding of steel tube properties, tube failure limits, frictional effects, and the entire tribological system important in tube hydroforming as well as the need for validated computer models and the need for design rules. This understanding is needed to facilitate the implementation of hydroforming in automotive and allow for the progression from mild steel to AHSS. This study is documented in (2).

Some early work comparing measured surface and thickness strains on the small scale simulation parts against forming limits established for sheet metal forming was conducted by Liu et al (3), Srinivasan et al (4) and Chen et al (16). These researchers showed reasonable agreement between experimental tube hydroforming strains and sheet forming limits.

Tube burst failure criterion was reported in a 2004 SAE paper by Chen, Moses and Soldaat (5). Proposed failure criterion were compared against experimental free expansion tube burst tests.

Significant work involved tests and methods to determine tube properties using conventional tensile tests of samples cut from tubes to account for strain/work hardening of the sheet steel during tube making, ring hoop tensile test (RHTT), and free expansion tube burst testing (1), (5). This work was analyzed and summarized by Zimmerman (6), (7).

Forming limits were examined with straight tube corner fill tests and friction was assessed using twist compression testing. Figures 1 and 2 illustrate these effects, respectively.

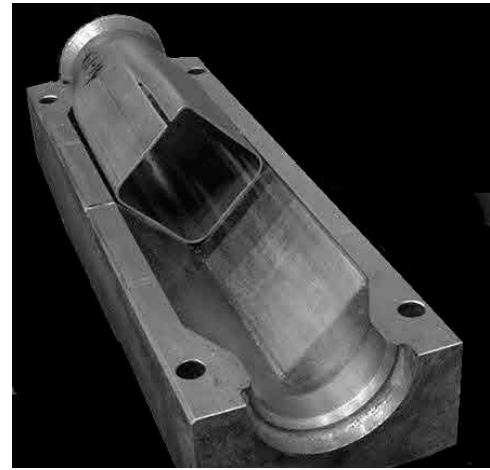


Figure 1: Straight tube corner fill test setup at IRDI

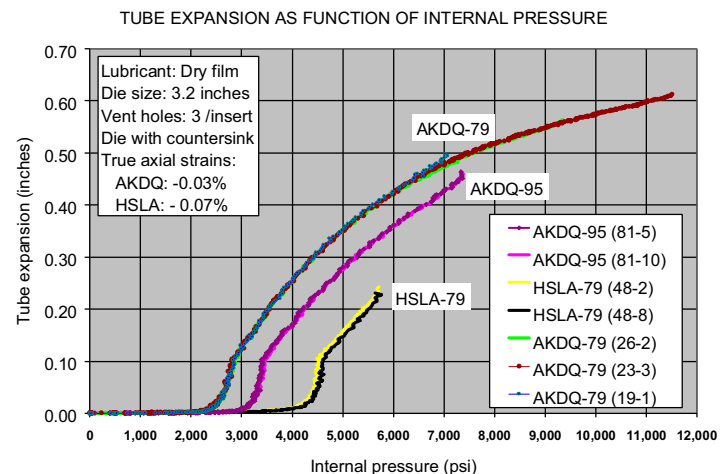


Figure 2: Straight tube corner fill test results exploring tube steel grade and thickness effects

The focus of this paper is to review three recent projects by the A/SP Hydroform Team. These projects have generated significant data that can be used to develop and validate analytical and FEA numerical computer models. These projects are:

1. Experimental Forming Limits of Steel Tubes (8), (9)
2. Effect of Bending and Lubrication on Hydroforming of IF and DP600 Steel Tubes (10)
3. Effect of Bending and Lubrication on Hydroforming of IF and DP600 Steel Tubes with Welded End Caps (11)

Reports, data and presentations are available for the first two projects in the Technology Transfer CDs (8), (10) and on the A/SP website (www.a-sp.org). Technology transfer CDs for project 3 will be available in the near future. (11) All three projects were contracted to IRDI.

Other current and active projects by the A/SP Hydroform team involve:

1. An extensive project to explore manufacturability of AHSS TWT for a hydroformed automotive front rail tube. Manufacture of the complex TWTs from

DP590 and DP780 of several different thicknesses was presented at the AISI 2007 Great Designs in Steel seminar (12). Bending and hydroforming trials are ongoing and results will be published in the future.

2. DP and TRIP tube seam Electric Resistance Welding (ERW) study.
3. DP and TRIP tube laser welding study.
4. Yield criterion study to generate data required for development of an accurate material model that accounts for strain path changes.

Finally, a fundamental project on Hydroforming of TWTs (13) contracted to IRDI was recently completed. This project included five TWTs configurations made from 1.2 mm and 1.5 mm of DP600 galvaneal (GA) sheet steel and 1.5 mm HSLA350 GA tested in free expansion and straight tube corner fill burst testing. The TWTs were also fully characterized for tensile mechanical properties.

EXPERIMENTAL FORMING LIMITS OF STEEL TUBES

The A/SP Hydroforming Team initiated a project to experimentally determine forming limits for steel tubes deformed through tube expansion with internal pressure and axial load, both tension and compression. This effort was designed to assess the applicability of the conventional forming limit diagram (FLD) developed for sheet metal stamping.

The project was conducted by IRDI and involved as-received 2.0 mm (0.0787 in) thick x 76.2 mm (3.0 in) outside diameter (OD) tubes made on a production electric resistance welded (ERW) continuous tube mill. Materials were AKDQ uncoated hot rolled (HR), interstitial free (IF) galvaneal (GA), and dual phase 600 MPa minimum tensile strength (DP600) GA. To study the effect of a change in strain path and pre-strain such as from bending prior to hydroforming AKDQ HR tubes were pre-strained with an axial strain of 11% and hoop strain of -4%. This level of strain simulates the strain on the outside of a 3.0 inch OD tube bent 90° around a 7.5 inch bend radius.

EXPERIMENTAL PROCEDURE - To generate an experimental forming limit curve (FLC), tubes were cut to a length of 227 mm for a length to diameter ratio of 3.0. These tubes were expanded along a number of quasi-linear strain paths through application of internal water pressure and axial force (tension or compression) to generate strain states from balanced biaxial tension to uniaxial tension. It was desired to stop the expansion at the onset of necking, but generally the expansion progressed to burst since it is extremely difficult to stop the test precisely at the point of necking. Necking strains from the tubes formed along different strain paths were measured from 2.54 mm diameter circle grids that were electro-chemically etched on the tubes to establish the forming limit curve (FLC). An algorithm

was used to determine necking strains from fracture strains for tubes that progressed to burst. Thickness was also measured around the circumference of some tubes at the location of maximum expansion to examine the thickness distribution and neck localization pattern.

EXPERIMENTAL TEST SETUP - A schematic and photograph of the experimental test setup is shown in Figure 3 and 4 respectively. Welded end caps are used to seal the tubes and for application of the axial load by hydraulic actuators. The tubes are expanded in free space through the application of internal water pressure and axial force which are controlled independently in a closed-loop system. The circumferential expansion and axial displacement are measured by linear variable displacement transducers (LVDTs).

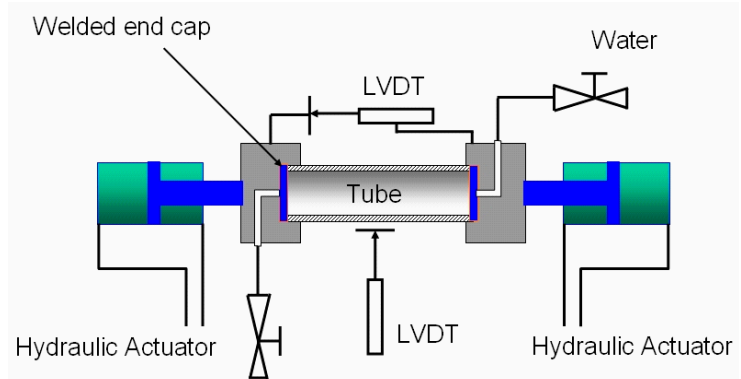


Figure 3: Schematic of Tube FLD Project Experimental Test Equipment

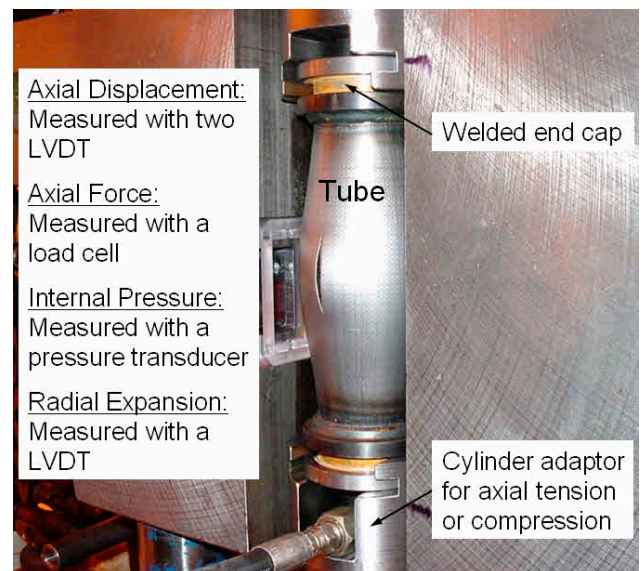


Figure 4: Photograph of Tube FLD Project Experimental Test Equipment

MATERIAL PROPERTIES FOR SHEET STEELS AND TUBES - Extensive analysis of tensile mechanical property characterization of the sheet steels and tubes used in the tube FLD project was conducted by Zimmerman (6), (7). A summary of the sheet and tube tensile mechanical properties are shown in Table 1 and free expansion burst test results in Table 2.

Table 1: Sheet Steel and Tube Mechanical Properties for FLD Project

		Test Direction	Location Relative to Weld (° measured counterclockwise)	Specimen Type	Yield Strength (0.2% offset YS) (MPa)	Ultimate Tensile Strength, UTS (MPa)	Uniform Elongation (%)	Total Elongation (%)	n-value (10% to 20% or uniform elongation)
AKDQ HR	Sheet	0° (long.)		Full size	221	340	23.4	44.5	0.226
				Sub size	224	347	25.5	48.8	0.228
	Sheet	90° (trans.)		Full size	246	341	23.8	44.8	0.231
				Sub size	240	348	25.0	48.4	0.230
	Tube	0° (long./axial)	45°	Sub size	247	355	23.6	48.8	0.202
			90°	Sub size	238	354	23.9	48.7	0.207
			135°	Sub size	258	355	22.9	49.6	0.198
			180°	Sub size	276	356	22.5	48.4	0.188
			225°	Sub size	251	355	23.8	49.9	0.201
			270°	Sub size	243	351	23.5	50.7	0.205
			315°	Sub size	252	355	22.7	50.1	0.201
	Tube	90° (trans./hoop)	90° (9 o'clock)	Sub size	233	353	25.1	49.1	0.217
			180° (6 o'clock)	Sub size	250	353	23.4	53.9	0.208
			270° (3 o'clock)	Sub size	223	352	24.4	45.6	0.216
IF GA	Sheet	0° (long.)		Full size	152	306	23.1	46.7	0.228
				Sub size	157	310	25.3	51.9	0.237
	Sheet	90° (trans.)		Full size	164	309	23.5	47.5	0.225
				Sub size	168	313	24.6	52.1	0.233
	Tube	0° (long./axial)	45°	Sub size	215	311	23.9	53.1	0.209
			90°	Sub size	214	312	24.2	53.4	0.211
			135°	Sub size	228	311	24.1	52.5	0.202
			180°	Sub size	250	313	22.6	52.2	0.189
			225°	Sub size	224	313	24.1	53.2	0.205
			270°	Sub size	211	312	24.8	52.2	0.212
			315°	Sub size	219	312	23.1	52.8	0.207
	Tube	90° (trans./hoop)	90° (9 o'clock)	Sub size	198	310	23.6	51.0	0.212
			180° (6 o'clock)	Sub size	232	313	23.5	50.5	0.196
			270° (3 o'clock)	Sub size	205	314	24.0	51.0	0.213
DP600 GA	Sheet	0° (long.)		Full size	363	632	15.3	26.6	0.151
				Sub size	367	638	15.4	27.6	0.150
	Sheet	90° (trans.)		Full size	383	649	14.3	24.8	0.146
				Sub size	383	652	14.8	27.5	0.150
	Tube	0° (long./axial)	45°	Sub size	463	656	13.3	27.1	0.123
			90°	Sub size	481	657	13.6	28.0	0.131
			135°	Sub size	478	658	13.0	28.2	0.127
			180°	Sub size	469	651	12.8	26.4	0.124
			225°	Sub size	477	657	13.3	27.7	0.125
			270°	Sub size	475	653	13.8	28.7	0.130
			315°	Sub size	474	657	13.1	28.2	0.127
	Tube	90° (trans./hoop)	90° (9 o'clock)	Sub size	434	654	12.8	24.5	0.144
			180° (6 o'clock)	Sub size	404	653	14.9	28.9	0.144
			270° (3 o'clock)	Sub size	407	652	14.2	27.7	0.141

Notes: (1) Full size sheet results are an average of 6 tests in the 0° (long.) direction and 2 tests in the 90° (trans.) direction.
(2) Sub size sheet results are an average of 28 tests in the 0° (long.) direction and 6 tests in the 90° (trans.) direction.
(3) Tube results are an average of 2 tests per combination of direction and location.

(Note: See Appendix for larger version of Table 1.)

Table 2: Free Expansion Tube Burst Test Results

Material	Expansion at Failure %	Max Pressure MPa
AKDQ HR	34.8	21.36
IF GA	28.6	20.66
DP GA	12.6	39.87

Results are an average of 3 tests per tube material.

EXPERIMENTAL RESULTS - The experimental test equipment and procedures used were able to expand the tubes along a number of quasi-linear strain paths such as shown for AKDQ HR in Figure 5. It was, however, found that the strain paths progressed linearly along the target strain ratio at the start, but moved toward plane strain as the test progressed.

The tubes were expanded to failure and consistently exhibited a split or neck that was parallel to the tube weld seam (i.e., along the length of the tube), but not in the weld seam or heat affected zone (HAZ). In some cases it was possible to stop the test at the point of necking just before splitting. For example, Figure 6 shows the distribution of major principal strain (circumferential/hoop direction), minor principal strain (longitudinal/axial direction) and thickness strain around the circumference at the section of maximum expansion for an IF GA tube that exhibited a shallow, detectable neck.

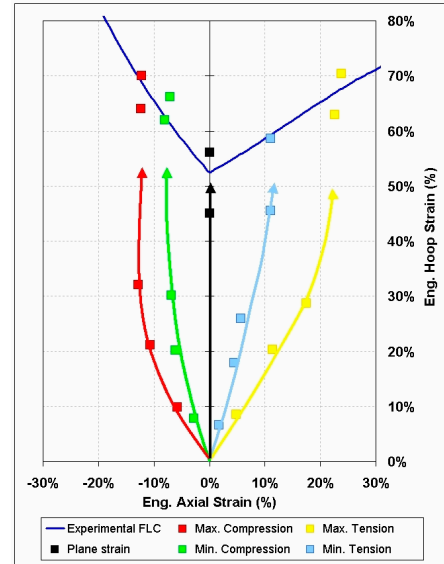


Figure 5: Strain paths for AKDQ HR

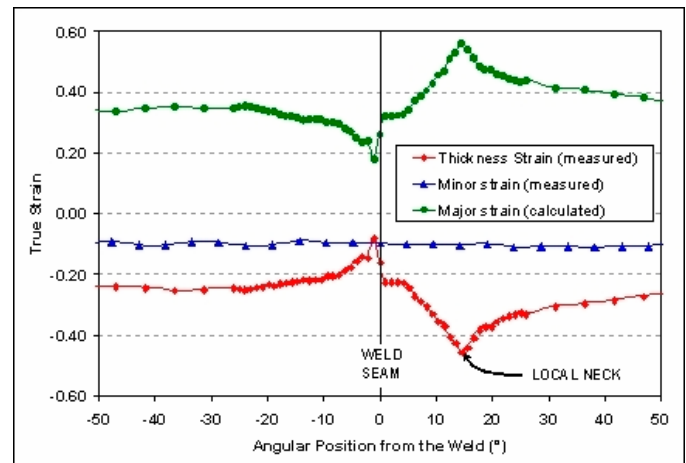


Figure 6: Example of principal strain distribution in the section of maximum expansion for an IF GA tube that exhibited a shallow detectable neck

As Received Tube FLDs - An experimental FLD was generated for each of the three materials by fitting a FLC defined as the strain states at the onset of incipient necking. Therefore, the experimentally fit FLC attempts to have all safe data points lie below the FLC and all necked and fractured points lie above the FLC.

The experimental FLD in each case is compared against the empirical Keeler-Brazier FLD for low carbon steel. The Keeler-Brazier FLC is a line of constant thickness strain on the draw/LHS of the FLD and an empirical polynomial fit on the stretch side/RHS of the FLD. The Keeler-Brazier FLC is positioned at the plane strain intercept (FLC₀) calculated as follows:

$$FLC_0 = n/0.21(23.3 + 14.13 \cdot t)$$

where, n = terminal n-value (strain hardening exponent)
t = thickness in mm

Figure 7, 8 and 9 show the results for AKDQ HR, IF GA and DP600 GA respectively. For all three tube materials the agreement between the experimental FLD and Keeler-Brazier FLD was very good. In all cases the Keeler-Brazier FLD was plotted based on FLC_0 using the average n-value from subsize longitudinal tube tensile specimens at the 45° and 315° locations from the weld.

Table 3 is a summary showing the comparison of the Keeler-Brazier FLC_0 and FLC_0 determined from the FLC fit to the experimental data. FLC_0 based on the sheet n-value over estimated the experimental tube FLC_0 in each case. The n-value from either the 0° (longitudinal/axial) or 90° (transverse/hoop) test direction provides good agreement for AKDQ HR and IF GA whereas using the 90° tube n-value for DP600 GA over predict by about 5 strain %.

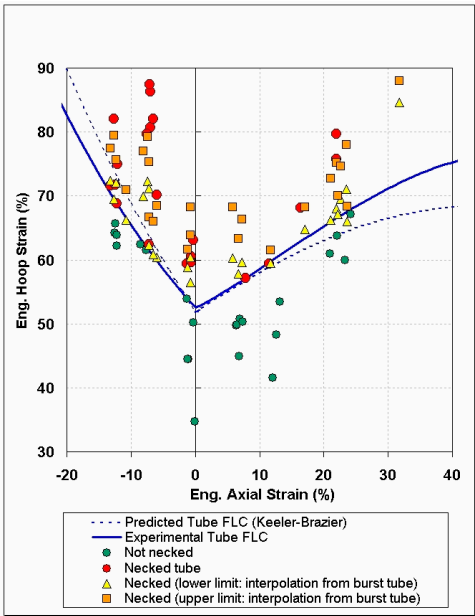


Figure 7: AKDQ HR

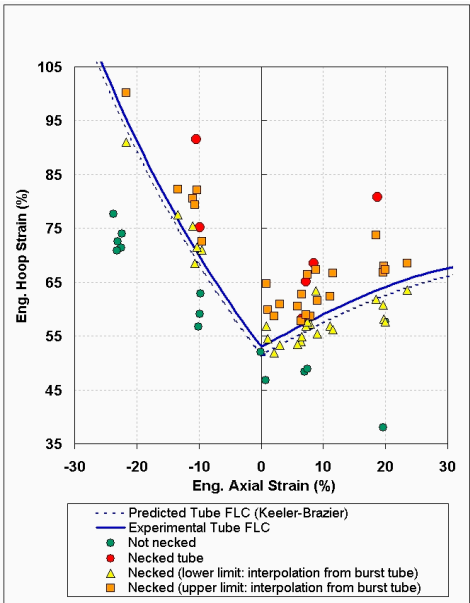


Figure 8: IF GA

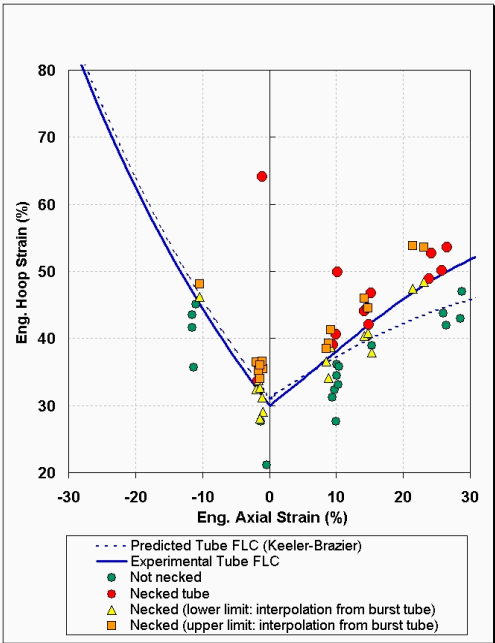


Figure 9: DP600 GA

Figures 7, 8 and 9: Experimental tube FLD for AKDQ HR, IF GA and DP600 GA compared with predicted Keeler-Brazier FLD

Table 3: Comparison of the Predicted FLC_0 and Experimental FLC_0

Material	Sheet or Tube	Thickness mm	Direction	n-value		Predicted FLC_0		Experimental Tube FLC_0 %
				Full-size	Sub-size	Full-size %	Sub-size %	
AKDQ HR	Sheet	2.13	0°	0.226	0.228	57.5	58.0	52.5
	Tube	2.13	90°	0.231	0.230	58.8	58.5	
		2.13	0°		0.202		51.3	
		2.13	90°		0.217		55.1	
IF GA	Sheet	2.02	0°	0.228	0.237	56.3	58.5	53.0
	Tube	2.02	90°	0.225	0.233	55.6	57.6	
		2.02	0°		0.208		51.4	
		2.02	90°		0.213		52.5	
DP GA	Sheet	2.05	0°	0.151	0.150	37.6	37.3	30.0
	Tube	2.05	90°	0.146	0.150	36.3	37.3	
		2.05	0°		0.125		31.1	
		2.05	90°		0.143		35.4	

Notes: (1) Tube sub size 0° n-value is an average of results at the 45° and 315° locations.
(2) Tube sub size 90° n-value is an average of results at the 90° and 270° locations.

Experimental FLD for Pre-strained Tube - Pre-straining AKDQ HR tube to simulate tube bending prior to hydroforming was found to have a dramatic effect on the FLC. The experimental FLC generated with 11% axial and -4% hoop pre-strain for this material is shown in Figure 10. The strain paths followed to generate the FLD are shown in Figure 11.