AADE-11-NTCE-30

Development and Metallurgical Testing of New Spherical Gripping Technology vs. Traditional Die Slips

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Abstract

Presents a new pipe gripping method using spherical balls to replace conventional die slips with the potential for significantly less damage to and better load distribution around pipe during handling. Describes the testing scope, results and analysis of ball versus slip comparison testing conducted under identical conditions.

Introduction

A primary goal during tubular handling is to minimize imparted damage that can produce subsequent pipe degradation or failure. This is particularly important for production pipe like casing or tubing. Die slips have long been used in various applications for pipe handling, all of which depend on slips fitted with replaceable steel die teeth that embed slightly into the pipe wall when fully engaged. This method subjects pipe to widely recognized yielding and technical limitations, but until now better alternatives haven't existed and die slip limitations were reluctantly tolerated.

We present a new gripping technology that uses spherical balls in tapered pockets to replace die slips to keep casing round in the vicinity of the gripping surface and with potential to reduce pipe damage. This new ball-and-pocket gripping technology uses spherical balls in tapered pockets to replace die slip teeth and minimize damage impact, leaving pipe in its most robust condition after handling. Extensive metallurgical comparison testing of balls versus die slip teeth shows dramatic reduction along several key metrics, like hoop strain and localized stress concentration levels.

In the current drilling environment, operators are searching for technological improvements to extend wellbore life and accommodate increasingly heavier loads while minimizing pipe yielding limits. The new ball gripping technology has applicability for all pipe handling applications to leave pipe in its best possible condition after handling and demonstrates the potential ability to change how pipe is handled in our industry.

Comparison Testing Protocol

Comparison load testing was conducted between the new ball-and-pocket pipe handling technology and conventional die slip teeth. The new technology uses dozens of stainless steel balls within individual tapered pockets to replace die slips that have been used for years. Slip-crushing tests were to be conducted with both gripping methods engaging the OD of instrumented casing pipe with specified nominal dimensions of 7.00” OD and 5.72” ID (44 lbs/ft). For comparison, a conventional slip system was also tested on instrumented casing pipe with the same nominal dimensions.

A detailed test procedure was developed with the intent to have the new technology's balls land directly over strain gauge rosette locations on the ID and then within ½” of every possible strain gauge location. Similarly, with the die slips, the goal was to have the slips bite within 5 degrees of every possible strain gauge to slip insert relative position around the hoop plane. Both of these were accomplished by precisely moving the gripping mechanism relative to the pipe. While testing was ongoing the data was reviewed in real time and the test was altered as needed to preserve gauge integrity and provide a fair, sustained evaluation of the strains at each relative position.

Test Plan Development

Slip-crushing tests are designed to emulate the loading experienced by drill pipe or casing as it is gripped and lifted by slips during drilling applications. However, the loading process during laboratory testing differs in some respects from typical field usage on a rig. In the test laboratory, the loading set-up includes the following considerations:

1. The casing pipe is held fixed via slip system and the load is applied by raising the test assembly either by pushing up on the bowl for the conventional slips or by pulling up via a crossover to the new technology's top assembly.
2. Increasing the axial load to maximum levels occurs gradually over a period ranging from one to three minutes in the laboratory, whereas this will occur on a rig in a matter of seconds (or less).
3. Strain measurements are recorded for the duration of the load cycle.

4. The maximum load is held long enough to stabilize, which allows any settling due to friction to stabilize at the actual applied load.
5. Dynamic loading events, tolerances, equipment wear, and other variable field conditions (cleanliness, surface conditions, load transfer speed, harmonics, torque, drag, internal pressure, external pressure, fatigue, etc.) are not emulated during this laboratory test program.

The test plan called for the ball technology assembly to be axially loaded to a load up to 500 tons. The test plan was modified during the tests based on the strains measured on the casing pipe. The maximum load for all loading cycles was dictated by the maximum strain/VME stress in the pipe, which was limited to approximately 80 ksi. Testing was initiated with the split line of the split coupling on the assembly oriented at 0°. After the first load cycle, the device was raised ½", loaded, raised another ½", and loaded, for a total of three loading cycles at the 0° orientation. Next, the tool was rotated 5° and the three load cycles were repeated. The tool was then rotated again to the 10° orientation, and the three load steps repeated. In summary, the ball technology assembly was subjected to nine load cycles—three load sets at an orientation of 0°, 5°, and 10°. During the last loading cycle, the prescribed maximum VME stress of 80 ksi was first achieved and held per the procedure. The axial load was then increased to the maximum of what was deemed to be a safe load that would severely load the pipe, but avoid pulling it into two pieces.

The exemplar four-section floor slip device, representative of conventional slips, was tested similar to the ball technology assembly. The original test plan for the conventional slips called for pulling up to 500 tons; however, the testing was again modified during the test to include monitoring the strains measured on the casing pipe as loading progressed. The common maximum VME stress to be attained for each load cycle for this pipe was based on limiting the highest measured strain/VME stress to approximately 70 ksi. Multiple load cycles were applied to the slips. Positions of the slips differed from those of the ball device; for the slips, the tool was rotated in 5° increments through a total of 75°. The conventional slips were not raised on the casing pipe. Sixteen repetitive load cycles were completed on the conventional slip assembly, plus a final load cycle to a high load where the load achieved was limited by safe testing practice, not stresses in the pipe.

The ball technology uses spherical balls in tapered pockets as its gripping mechanism to impart discreet loading areas. This device was raised and lowered to help locate a ball as near as possible to or directly above a strain gage on the ID of the casing, allowing the effects of the discreet loading areas to be observed. In contrast, conventional slips have a long bite length. This bite length is continuous over the length of the tool but is segmented around the circumference of the tool. For the conventional slips, the tool was rotated to allow relative movement between the strain gage location and the insert dies/slip segments into locations where the effects of the segmentation of the tool could be observed.

Sample Preparation

The sample casing pipes for these slip-crushing tests were fabricated from a section of nominal 7″ × 0.64" WT C-95 casing. The goal of a slip-crushing test is to quantify the stresses expected for any given piece of casing of the dimension under test. To represent what would be expected for a randomly selected pipe placed in these slips in the field, it was decided that nominal conditions were preferred for the test pipe. Correspondingly, the OD and ID of the casing pipes were machined to nominal dimensions of 7" OD × 5.72" ID (44 lbs/ft).

Strain-gage rosettes were attached to the ID and OD surfaces of the sample pipes. The strain gages were arrayed in seven rows (or rings) with five rosettes spaced equally around the circumference of each row. Identical clocking of the rosette locations was maintained on both OD and ID; thus, there were five columns of rosettes in and on the test pipes. The rows of rosettes were spaced to encompass the area where the slips/balls were actually biting.

Axial spacing of the rosettes was begun with the OD rosettes, which were attached on one row about ¼" to ⅜″ below where the toes of the slips were expected to bite. On the ID of the pipes, the bottom row of rosettes was positioned about ⅜″ to ½″ above the actual height of the lowest insert die tooth or ball. The heights for the other five rows of rosettes on the pipe ID were spread to cover the remainder of the slip region.

To prepare the sample for application of the strain-gage rosettes, localized light grinding was required on the ID and OD at the gage locations. All gages were attached at their respective positions on the pipe OD using M-BOND 200 cyanoacrylate cement.

Slip Crushing Tests

Test Procedures

A series of load cycles was to be completed as each test article gripped on its sample casing. The load testing plan for the ball technology assembly was as follows:

1. Set and mark the relative orientation of the handling equipment, with 0° defined to align with the split line of the split ring on the assembly and with the split line of the bowl on the conventional slips.
2. Load the tool axially up to 500 tons (1000 kip) or until the highest calculated von Mises equivalent (VME) stress in the casing pipe approached 80 ksi. The VME stress limit was based on the C-95 casing material and a desire not to permanently yield the casing sample. VME stresses were calculated and monitored in real time for each strain gage.
3. When a VME stress of 80 ksi was observed at any of the strain gages, that load was held for approximately 1 minute, long enough to stabilize any gross deflection of the handling equipment/test sample and load frame system.
4. Reduce the load to zero. Raise the assembly on the casing pipe by ½".

5. While monitoring VME stresses, repeat loading to the same maximum load as in step 2, or to a lower load if a VME stress reaches 80 ksi prior to achieving the initially established load.
6. Reduce the load to zero and raise the assembly another ½" and repeat loading steps above.
7. Reduce the load to zero and rotate the assembly 5° and repeat the load steps above with the assembly being lowered ½" after each load step.
8. After three load tests on the 5° location, rotate the assembly another 5° and repeat the load steps above, for a total of nine loading events.

The loading plan testing for the Conventional Slips was as follows:

1. Set and mark the relative orientation of the slips, with 0° defined to align with the split line of the bowl of the slips.
2. Load the slips axially up to 500 tons (1000 kip) or until the highest calculated VME stress in the casing pipe approached 70 ksi. (This maximum allowable stress was lower than was used for the ball technology tests, a decision based on our experience with slip-crushing tests. It was expected that there would be more scatter in the hoop strains/VME stresses using conventional slips, and a lower maximum strain would provide a larger safety margin.) The VME stress limit was based on the C-95 casing material and a desire not to permanently yield the casing sample. VME stresses were calculated and monitored in real time for each strain gage.
3. When a VME stress of 70 ksi was observed at any of the strain gages, that load was held for approximately 1 minute, long enough to stabilize any gross deflection of the handling equipment/test sample and load frame system.
4. Reduce the load to zero. Pick up and rotate the slip through 5°.
5. While monitoring VME stresses, repeat loading to the same maximum load as in step 2, or to a lower load if a VME stress reaches 70 ksi prior to achieving the initially established load.
6. Continue rotating the slips by 5° and applying axial load as above until a total of 75° of rotation has been achieved.

Ball Technology Testing

Slip-crushing tests with the ball technology assembly were completed using the test setup shown in Figure 1. The goal was to determine the orientation that corresponded to the highest strains in the casing for a given total load. The procedure was to load the device to 500 tons (1000 kip) or until ~80% of yield stress was measured via one or more strain gages on the casing, whichever was lower. During the initial loading sequence at Position 1 and 0° angle, the loading was stopped at 471 kip based on a stress of 81 ksi measured at strain gage rosette 11. Minimum yield strength of the casing is 95 ksi; loading was halted below that level so that no permanent yielding of the casing sample would occur. A series of loadings was then completed as the assembly was rotated and raised to allow for a total of nine different positions. A second run at the final position was conducted at the end of the test to investigate the maximum capacity of the tool, but without surpassing loads that the test pipe could support without danger of being pulled into two pieces.

Fig. 1. Ball technology assembly installed in test load frame

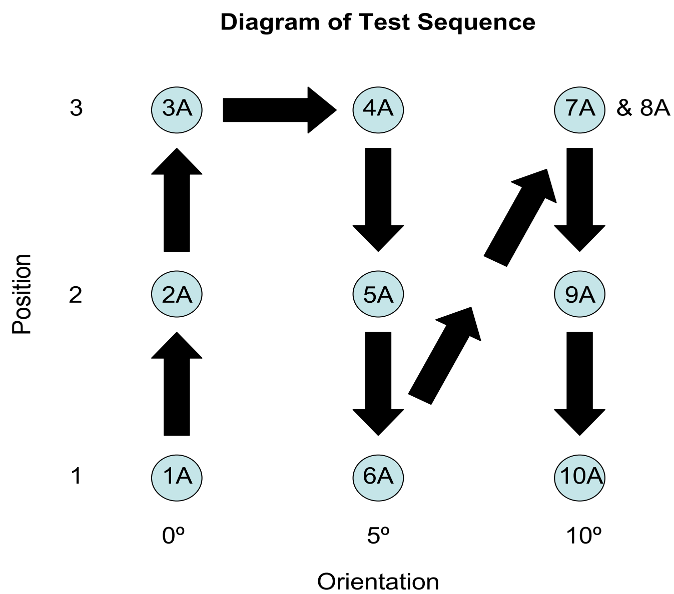

Fig 2. Diagram of ball technology testing sequence

Testing was initiated with the split line of the split coupling on the assembly oriented at the 0° column of rosettes on the pipe. VME stresses of all strain gages were monitored in real time as load was increased. After the first pull to 471 kip, the assembly was unloaded and the device was raised by ½". Load was then applied until either 471 kips was reached or one or more strain gages recorded stresses near 81 ksi. In case the latter occurred, the reduced frame load would then be noted and used as the limit in subsequent load cycles. There are two deviations from the approximately 471 kip loading condition discussed in the next paragraph. The loading process was repeated after raising the tool another ½" up the casing pipe. After the three load tests at the 0º position were completed, the device was rotated 5° and the loading sequences described above were repeated. After test 6A—the third load test at the 5° position—the tool was rotated to 10º and another three load steps completed.

The second load test at position 1 at 10° was allowed to go beyond the 470 kip load limit to determine the maximum load that could be placed on the pipe sample. Loading was stopped at 858 kip based on load versus displacement data, which began to indicate yielding in the casing test pipe. The other deviation from the 470 kip load limit was on load pull at position 3 at 10°. There was a false start that only reached 136 kip. (It turned out that this was a fortunate coincidence that allowed direct comparison between loads induced by the ball technology tool and the conventional slips. See the Conclusions section for discussion.

Data from these 10 initial loadings of the ball technology assembly are summarized in Table 1.

Table 1. Load testing of ball technology assembly at various orientations

Test #	Orientation[1]	Max VME Stress (ksi)[2]	Strain Gage	Load (kip)
1A	1 – 0°	81	11	471
2A	2 – 0°	57	11	471
3A	3 – 0°	77	13	472
4A	3 – 5°	81	11	474
5A	2 – 5°	72	11	471
6A	1 – 5°	81	11	394[3]
7A	3 – 10°	32	16	136
8A	3 – 10° (second run)	81	16	463
9A	2 – 10°	75	11	477
10A	1 – 10°	417	5	858

[1] Orientation is relative to split line in the split coupling.
[2] All stresses reported are based on the assumption of linear elastic behavior
[3] Minimum load required to achieve a VME stress near maximum target range of 80 ksi.

Responses from all strain gages were recorded for each orientation during the load sequences. As an example, a summary of the maximum strains measured at the position 1 at 0° orientation during this initial load test to 81 ksi VME is shown in Figure 3.

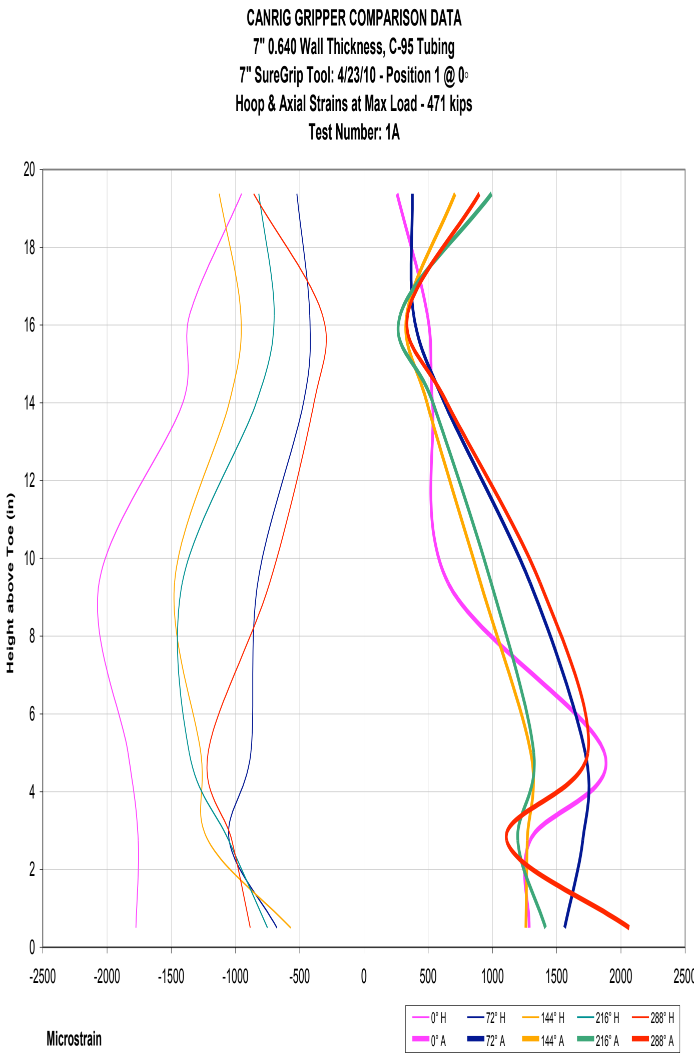

Fig. 3. Maximum strains for all stain gages during initial loading to 471 kip at position 1 with 0 degree orientation

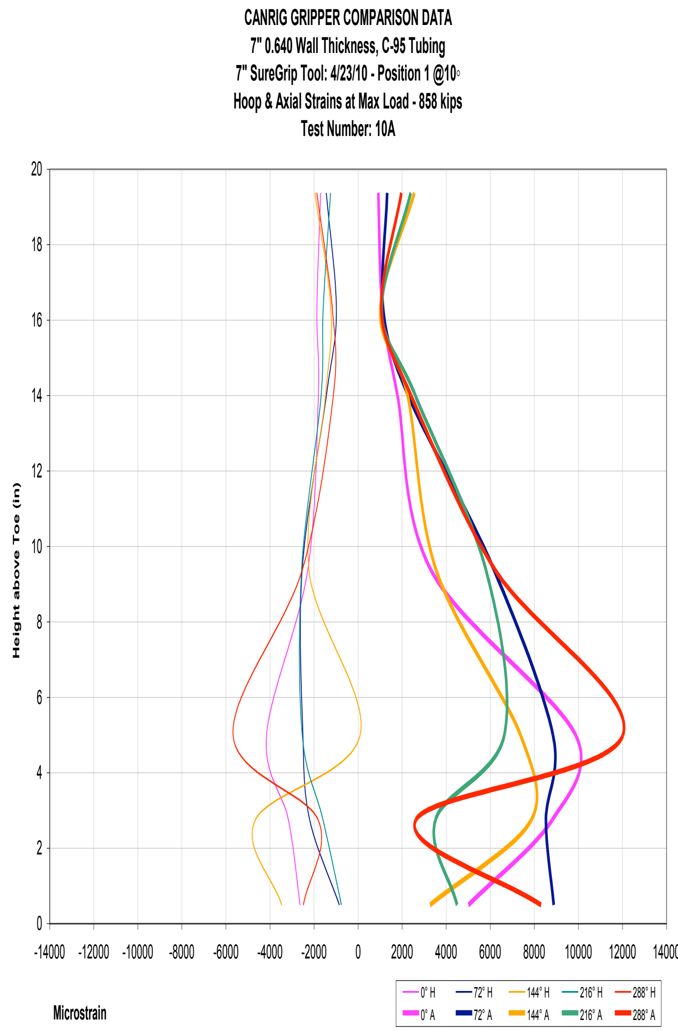

Fig. 4. Maximum strains during high load cycle to 858 kip

In the final high load step, the load was gradually increased toward the ball technology device's rated maximum working load of 1000 kip. The team decided that loading should not be increased past 858 kip due to observed indications of yielding in the casing test pipe in the real-time load versus displacement data. The test frame was not set up to safely handle a failure event should the pipe be pulled into two pieces. At this point, the team agreed that the load should be reduced and the test considered complete.

Maximum strains measured during the high load cycle to 858 kip are shown in Figure 4. Note that the hoop strains are large in magnitude and negative in direction because the pipe is being squeezed down in net diameter by the tool. The axial strains are tensile and tend to be highest at the toe or just above the toe, and then diminish toward the top of the slips. This is expected because the full tension on the pipe is present near the toe but diminishes to zero at the top of the tool.

Conventional Slip Testing

Testing of the conventional slips and its sample casing was completed using the test setup shown in Figure 5. As with the ball testing, the procedure was to load the conventional slip to 500 tons (1000 kip) or until ~75% of yield stress was measured via one or more strain gages on the casing, whichever was lower. During the initial loading sequence at Position 0°, the loading was held at 271 kip based on a stress of 71 ksi indicated for strain gage rosette 1. This maximum allowable stress was lower than was used for the ball tests, a decision based in part on our experience with slip-crushing tests. It was expected that there would be more scatter in the hoop strains/VME stresses using conventional slips. The casing sample had minimum yield strength of 95 ksi and the load was limited to 71 ksi so that no permanent yielding of the casing sample would occur. A series of loadings was completed as the slips were rotated through 75° in 5° increments. A second load cycle was performed at the final position at the end of the test, for a total of 17 load sequences. For the final loading, the goal was to reach at least ~858 kip if that could be achieved safely. This would allow a direct comparison between the damage done by the ball technology assembly and a representative conventional slip.

Fig. 5. Conventional slips installed in small load frame

Testing was initiated with the split of the conventional slip oriented at the 0° column of rosettes on the pipe. After the first load cycle, the assembly was unloaded and the slips picked up and moved 5° to the next position. Load was then applied until either the load reached 271 kip, or one or more strain gages recorded stresses near 70 ksi. This process of load, unload, and rotate was repeated for every 5° until a total rotation of 75° had been achieved.

After the conventional slips had been load tested 16 times, loading was repeated at position 75° to a maximum of 884 kip to closely match the 858 kip load placed on the ball device. Performance of the ball technology and conventional slip tools is compared in the Conclusions section.

A review of the data from the 17 load tests shows that, as the tests progressed, a lower load was needed on subsequent tests to achieve a VME stress near 70 ksi. Maximum VME stresses and the corresponding strain gage locations are listed in Table 2.

Table 2. Load testing of Conventional Slips at various orientations

Test #	Orientation[1]	Max VME Stress (ksi)[2]	Strain Gage	Load (kip)
1B	0°	73	1	271
2B	5°	69	1	273
3B	10°	73	27	190
4B	15°	74	16	160
5B	20°	74	11	155
6B	25°	61	30	138
7B	30°	68	25	139
8B	35°	55	25	140
9B	40°	57	1	139
10B	45°	63	1	143
11B	50º	63	1	138
12B	55º	87	1	140
13B	60º	80	1	142
14B	65º	81	1	138
15B	70º	94	1	138
16B	75º	98	1	130[3]
17B	75º (Second Run)	263	26	884

[1] Orientation is relative to split line in the conventional slip tool.
[2] All stresses reported are based on the assumption of linear elastic behavior
[3] Minimum load required to achieve a VME stress near maximum target range of 70 ksi

Responses from all strain gages were recorded for each orientation during each load sequence. As an example, a summary of the maximum strains measured at the 0° orientation during the initial load test to 70 ksi VME is shown in Figure 6.

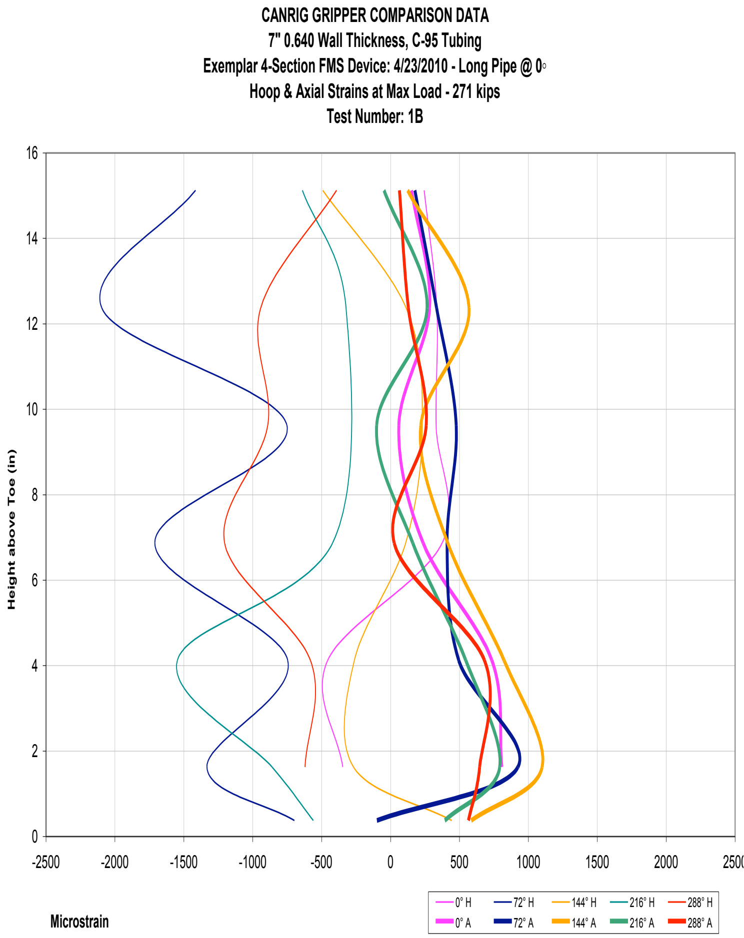

Fig. 6. Maximum strains for strain gages during initial loading to 271 kip at 0° orientation

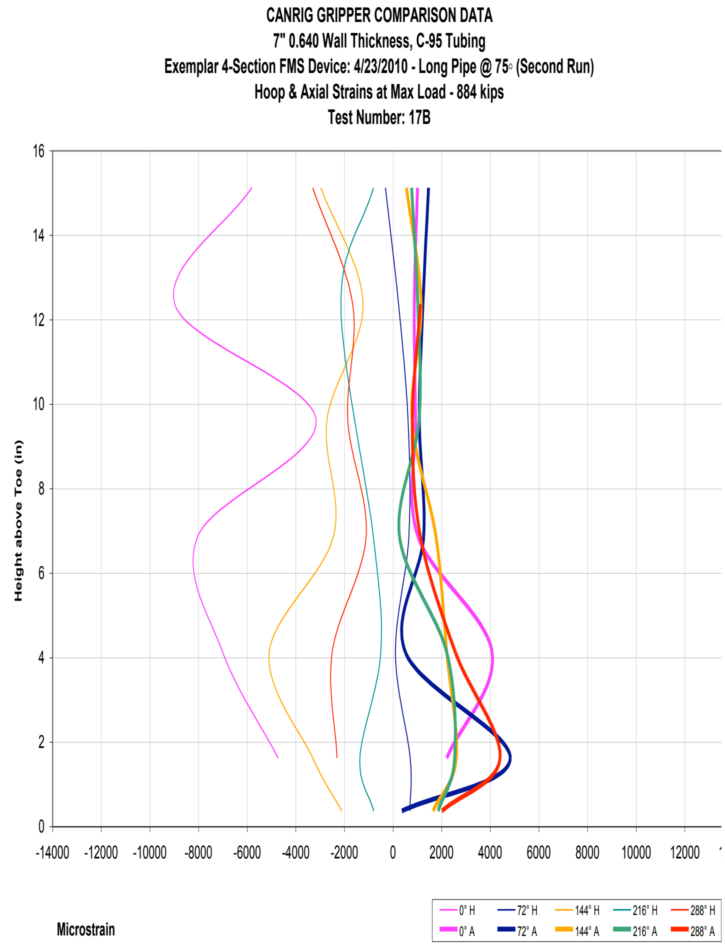

Fig. 7. Maximum strains for strain gages during high load cycle to 884 kip

Maximum strains measured during the high load cycle to 884 kip are shown in Figure 7. Generally, the hoop strains are large in magnitude and negative in direction because the pipe is being squeezed down in net diameter by the slips. However, there is significant scatter in the magnitude of the hoop strains because the hoop is being deformed from round to some other shape that the slips are forcing on it. Axial strains are tensile and tend to be highest at the toe or just above the toe, and then diminish toward the top of the slips. This is expected because the full tension on the pipe is present near the toe but diminishes to zero at the top of the slips.

Conclusions

Comparison of the strain data and recorded effects on the test pipe sections by the two gripping technologies yields the following observations:

1. The ball device produces a well-behaved pattern of strains in both the axial and hoop directions in its interaction with the casing and almost all hoop strains are compressive. The conventional slips produce relatively well-behaved strains in the axial direction, but the hoop strains were not well behaved, with wide scatter indicative of bending around the hoop.
2. The ball technology produced a slower rate of hoop strain increase per unit of increased axial loading on the casing pipe than did the conventional slips, resulting in 200 – 400% less hoop strain as measured on the pipe ID.

These observations are discussed in greater detail in the paragraphs below.

Regarding axial strains, data for both tools show a similar and well-behaved pattern. The data sets for both tools show an average net positive strain in the axial direction, which correlates to a net tension on the casing pipe due to axial loading. Axial strain data for both tools are relatively tightly clustered for each column of rosette locations around the pipe. Also, both tools induce the highest axial loading at or near the toe of the device, with the magnitude of the strain diminishing toward the top of the device. This is expected in that the full axial load is being supported at the cross-section of the casing just at/below the toe, while the axial load being supported diminishes toward zero at the top of the tool.

Regarding hoop strains, behavior is notably different for the two tools. For the ball device, the hoop strain data show a more tightly clustered net compression at the ID of the casing. This is consistent with the casing pipe being squeezed in the hoop direction in a near-uniform manner throughout the engagement length. This is likely due to the high number of loading points around the mechanism, each of which is free to apply a radially oriented gripping force. In contrast, the conventional slips show a much less consistent pattern in hoop strain. The data are not closely grouped as was observed with the balls. Some strain gages on the conventional slips measured a net positive strain on the ID of the casing pipe, which indicates bending of the casing pipe. This type of bending would be the result of deformation of the circular cross-section as it conforms to the gripping of the slips. The slip sections apparently force the pipe to conform to the shape of the relatively thick (or rigid) gripping section. Since there are only four sections, each loading radially inward at the center of that particular slip section, the pipe must conform such that there are multiple points of bending around the pipe section. Therefore, the superposition of a net hoop compression plus bending around the hoop yields a hoop strain distribution with much more scatter than the ball device.

Figures 8 and 9 show the strain data for test number 7A (ball technology to 136 kip) and 6B (conventional slips to 138 kip), respectively. As mentioned, Test 7A was a false start on the ball test that was stopped at 136 kip. These two load cycles allow for a direct comparison at an equal loading state between the two tools. Axial strain data on the ball device (Fig. 8) are well behaved, with a maximum axial strain of less than 1000 με. Axial strain data for the conventional slips (Fig. 9) are also well behaved, with a maximum strain of less than 1000 με. Data for the hoop direction on the ball technology show a well-behaved pattern, with a maximum hoop strain of near 500 με. However, hoop strain for the conventional slips are not well behaved, with two of the hoop strain gages (288° and 144° positions) showing net positive strain and the other three positions showing net negative strain. The maximum magnitude of the hoop strain was greater than 2300 με in the negative direction and greater than 1500 με in the positive direction.

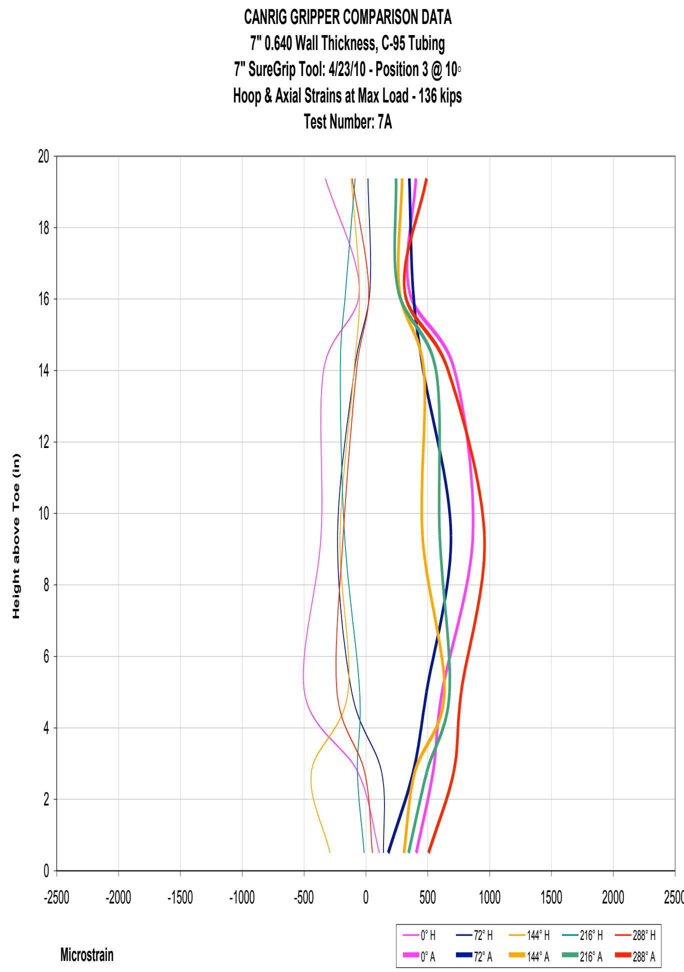

Fig. 8. Test 7A – Ball technology strain data at a load of 136 kip

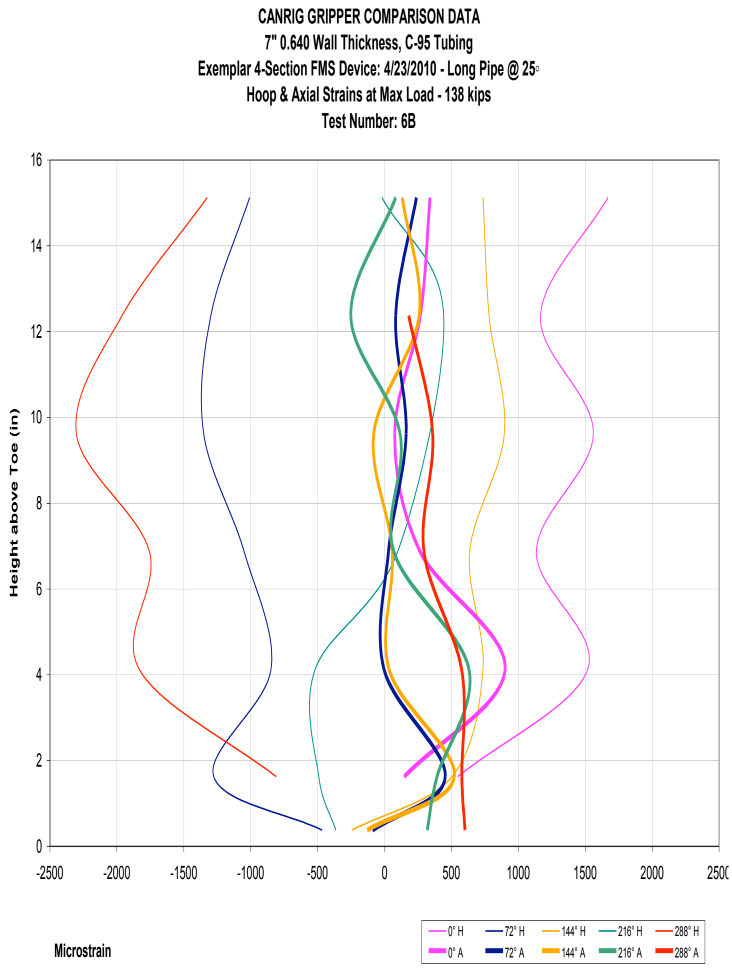

Fig. 9. Test 6B – Conventional slip strain data at a load of 138 kip

The third observation is regarding the rate of increasing strain/VME stress per unit of increase in the axial load. Tests 7A and 6B showed that the rate of increase in *axial* strain due to *axial* loading is very similar for both tools. The rate of change in *hoop* strain is very different for the two tools. The ball device shows a maximum strain of about 500 με for 136 kip of axial loading, or about 3.68 με per kip. The conventional slips produced a maximum strain of about 2300 με for nearly the same axial loading (138 kip), corresponding to 16.7 με per kip. If one considers the average magnitude of the hoop strains in the ball technology tool, it is about 2 με per kip, whereas in the conventional slips, it is approximately 7.97 με per kip.

Comparison at these relatively low loads may be somewhat suspect. However, if the comparison is repeated for more typical test loads of ~470 kip for the ball device and ~270 kip for the slips, maximum hoop strain is near 2000 με (~4.25 με/kip) for the balls and about 1500 με (~5.56 με/kip) for the conventional slips even at much lower loads. These data indicate that the ball technology has a lower average and maximum rate of increase of hoop strain per unit of axial loading than does the exemplar tool.

Acknowledgments

Special thanks to the following individuals who led scope development, execution, and final analysis of this testing project:

Faisal Yousef, Canrig Drilling Technology Ltd.
Kurt Vandervort, Stress Engineering Services
Scott Wharton, Stress Engineering Services