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Developments in Coiled Tubing BOP Ram Design

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Abstract

Significant technical improvements have been made recently in the design of coiled tubing (CT) blowout preventer (BOP) shear and slip rams. This technology is constantly being enhanced and refined as the CT service industry continues to mature and new operational demands are placed on the CT pressure control equipment. Larger CT sizes[1] require better BOP shearing capabilities. Advancements in the understanding of CT fatigue life[2-5] have caused the life reducing affects of the slip ram markings on the pipe to be examined. This paper explores the circumstances that have precipitated these improvements, and the research and development methods involved in developing better BOP rams.

CT Shear Rams

The CT shear ram should be capable of shearing a specified range of CT with no tension in the string at maximum well head pressure[6], leaving a sheared portion of CT with a fishable top profile that has a residual outside diameter equal to or less than the original outside diameter. Equally important is the amount of flow area in the lower fish to permit sufficient circulation through the sheared CT to control the well during the well recovery sequence.

With the advent of operations with an electrical wireline installed inside of the CT, it has become an important design criteria that the shear rams cut not only a wide range of CT sizes but also stranded wireline inside the CT. The shear blades must be designed to eliminate any gap between the blades at the point of contact with the stranded wire to prevent trapping small diameter strands of the cable that would result in an incomplete shear. Also, the ability to repeatedly shear a wide range of sizes and weights of CT offers a definite advantage over previous designs of shear blades which required changing out blades for each size of CT.

Earlier designs of shear blades were lacking in their ability to perform multiple cuts, and to shear wireline. These designs typically had a "V" pocket configuration as is shown in figure 1, with a knife cutting edge fabricated from carburized carbon steel or hardened tool steel. These blades were generally limited to the smaller CT sizes up to 1-1/4" diameter used during that period. They were designed for a one time emergency cut and were to be replaced after each use due to their tendency to fracture on the first closure. Due to demand for a multiple cut blade and advances in CT metallurgy that propagated larger diameters and weights of CT, new innovations in blade design were required.

The radius pocket blade was introduced with a square cutting edge to overcome the shearing deficiencies of the earlier "V" blades. This concept proved successful

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References, tables and figures at end of paper.

in its' ability to repeatedly shear CT and wireline without damaging the blade's cutting edge. This was achieved by the radius pocket and blunt cutting edge, shown in figure 1, that allow the shearing compressive forces to be distributed over the entire cutting edge. Also, the radius pocket made a preferable cut that left an elliptical profile on top of the lower fish through which to circulate and easily fished with an overshot. This shear profile is repeatable with every shear allowing accurate planning of circulation rates and of overshots required. The radius blades also feature extended blade guides to facilitate a clean cut of stranded cable. As the rams come together, these guide extensions "sandwich" between the opposing blade and the blade pocket in the ram. This action prevents the deflection that occurs when the blade is under high shearing loads and does not allow the formation of a gap between the blades that can trap small diameter wireline or strands of braided cable. One drawback to this design is that it requires increased BOP ram hydraulic pressure to shear comparably sized CT over the knife edge design, and a specific blade size was essential for each diameter of CT.

As CT continued to increase in size and wall thickness, this requirement for increased hydraulic pressure became critical as larger sizes of CT pushed the limits of existing hydraulic supply pressure on many CT units. This made it necessary for development of a blade contour that retained the beneficial features of the radius pocket blade and would shear like sizes of CT with a reduced hydraulic pressure.

The development of the "RM" contoured blade has satisfied this requisite. The "RM" blade will shear a wide range of CT sizes without changing blades. This type of blade has been tested on a range of CT between 1.00" and 2.375" diameter, shearing a total of 25 separate sections of CT with the same set of blades. Comparison testing of both the radius style and the "RM" profile exhibits a reduction in hydraulic requirement of approximately 35% for the "RM" blade. Incorporation of this type of shearing mechanism, along with the addition of hydraulic booster cylinders, would give the operator maximum latitude and reliability to handle an entire range of CT at maximum wellhead pressures, using standard CT unit hydraulic sources.

Table 1 illustrates the differences in the BOP ram hydraulic pressure requirements for the RM and radius pocket shear blades. Columns 4, 5 and 6 list the hydraulic pressures needed to shear the specific size and weight of CT for well head pressures (WHP) of 0, 5,000 and 10,000 psi. Column 7 lists the hydraulic pressure required for a BOP with booster cylinders which boost the shearing force. The last column lists the actual shearing force needed to shear the CT.

CT Slip Rams

CT slip rams provide a means of gripping and suspending the CT, preventing vertical movement of the CT either upward or downward, without excessive damage to the CT. It is mandatory that slip rams be sized for each diameter of CT to effectively meet these requirements. The slip teeth may be bi-directional or a standard "V" thread profile that is hardened and will maintain a grip on the CT from both directions. Any slip design must demonstrate its' ability to perform in excess of the yield strength of the CT in both directions.

Early slip ram designs incorporated the hardened slip teeth machined into the ram itself. This would provide a large area of slip teeth for gripping, but was economically prohibitive due to the replacement costs of the entire set of rams when the slip teeth became worn, or when changing CT sizes became necessary.

The slip ram assembly with replaceable slip inserts had a definite advantage over the earlier designs due to its' inexpensive attribute of merely replacing the slip insert and CT guide when a pair of inserts became worn, or for conversion of the rams to a new CT size. A drawback of the slip insert would be the limited slip tooth area and the inherent problems of marking the CT that this concept would pose.

The progression of CT unit design and metallurgical improvements in the CT itself posed new problems for conventional slip rams. CT injection units were now available with hydraulic circuits capable of generating 3,000 PSI. Application of this kind of hydraulic pressure increases the probability of damaging the CT and crushing those sizes with thinner wall thicknesses. To overcome this obstacle, extended contact slip inserts were developed that would adapt to the existing ram body and possess a substantially greater slip tooth area, thereby reducing the unit load on the CT and the probability for deformation.

Until recently, it was common practice for the well operator to insist that the slip rams were tested for every job. It had been suspected for some time that this practice caused some amount of damage to the CT at each location the slips were closed and set. This resulted in numerous sections of CT retaining slip bite marks which could reduce the fatigue life of the CT string, particularly those with teeth marks that were continuous around the CT circumference.

These concerns prompted extensive series of tests[7] to determine how much these slip marks deteriorated CT performance, and assess the advantages offered by using alternative slip designs. Seven groups of 1.50" 70 grade CT were gripped by various designs of BOP slips and then subjected to tensile loading to 76% of their yield strength. Each of the specimens were then plastically bent (with no axial loading) while under internal pressure until failure occurred due to low cycle fatigue using the four point bending fatigue test machine shown in figure 4. This machine bends the CT sample in free space to cause plastic strain cycles. These cycles are not comparable to those to be expected on a coiled tubing unit.

Numerous samples of unmarked CT were tested on the rig at the same internal pressures to provide a direct comparison. Since fatigue tests produce a large amount of scatter, statistical methods were used in the data analysis. A safe working life was determined by standing off 3.1 standard deviations from the population mean estimated from a sample group thus giving a statistical failure rate of 1 in 1,000. Table 2 lists the results of some of this statistical analysis.

The tests concluded that in the worst case where a knife edge type mark was present around the CT circumference, average life was reduced by approximately 70% compared to unmarked CT, as is seen in the first two rows of table 3. In addition to reducing fatigue life, the pressure and tension limits are also reduced due to the smaller cross section of material and the residual stresses surrounding the notches.

These tests also found that slip designs that used an interrupted tooth profiles exhibited significantly longer fatigue life, as is shown in the last 4 rows of table 3. These slips, shown in figure 3 contain a series of vertical grooves spaced equally around the slip tooth circumference that reduces the stress riser marking on the CT. The latest innovations in slip design include this interrupted tooth profile.

Conclusions

New shear blades have been developed which allow multiple shear actions to be performed with one set of shear blades. These blades also reduce the hydraulic pressure needed to activate the BOP rams as compared to previous designs. New slip ram inserts have been developed with interrupted teeth which reduce the marking on the CT and thus have less impact on the fatigue life.

Acknowledgements

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CT O.D. (in)	CT Wall Thickness (in)	Blade Type	Hyd Pressure 0 psi WHP (psi)	Hyd Pressure 5,000 psi WHP (psi)	Hyd Pressure 10,000 psi WHP (psi)	Hyd Pressure with Booster Cylinder 10,000 psi WHP (psi)	Force (lbs)
1.000	0.075	Radius	1,600	2,156	2,711	932	11,310
1.000	0.075	RM	1,000	1,556	2,111	725	7,069
1.000	0.087	Radius	1,800	2,356	2,911	1,000	12,724
1.000	0.087	RM	1,100	1,656	2,211	760	7,776
1.000	0.095	Radius	1,950	2,506	3,061	1,052	13,785
1.000	0.095	RM	1,300	1,856	2,411	829	9,190
1.000	0.109	Radius	2,100	2,656	3,211	1,103	14,845
1.000	0.109	RM	1,400	1,956	2,511	863	9,897
1.250	0.087	Radius	2,000	2,556	3,111	1,069	14,138
1.250	0.087	RM	1,500	2,056	2,611	897	10,604
1.250	0.095	Radius	2,400	2,956	3,511	1,207	16,966
1.250	0.095	RM	1,500	2,056	2,611	897	10,604
1.250	0.109	Radius	2,800	3,356	3,911	1,344	19,793
1.250	0.109	RM	1,500	2,056	2,611	897	10,604
1.250	0.134	Radius	3,150	3,706	4,261	1,464	22,267
1.250	0.134	RM	2,400	2,956	3,511	1,207	16,966
1.250	0.156	Radius	3,600	4,156	4,711	1,619	25,448
1.250	0.175	RM	3,000	3,556	4,111	1,413	21,207
1.250	0.175	Radius	3,950	4,506	5,061	1,739	27,923
1.500	0.095	Radius	2,700	3,256	3,811	1,310	19,086
1.500	0.095	RM	1,700	2,256	2,811	966	12,017
1.500	0.109	Radius	2,900	3,456	4,011	1,378	20,500
1.500	0.109	RM	1,900	2,456	3,011	1,035	13,431
1.500	0.125	Radius	3,500	4,056	4,611	1,585	24,742
1.500	0.125	RM	2,100	2,656	3,211	1,103	14,845
1.500	0.134	Radius	3,800	4,356	4,911	1,688	26,862
1.500	0.134	RM	2,750	3,306	3,861	1,327	19,440
1.500	0.156	Radius	4,250	4,806	5,361	1,842	30,043
1.500	0.156	RM	3,200	3,756	4,311	1,481	22,621
1.750	0.109	Radius	3,200	3,756	4,311	1,481	22,621
1.750	0.109	RM	2,450	3,006	3,561	1,224	17,319
1.750	0.134	Radius	3,950	4,506	5,061	1,739	27,923
1.750	0.134	RM	3,000	3,556	4,111	1,413	21,207
1.750	0.156	Radius	4,600	5,156	5,711	1,963	32,517
1.750	0.156	RM	3,550	4,106	4,661	1,602	25,095

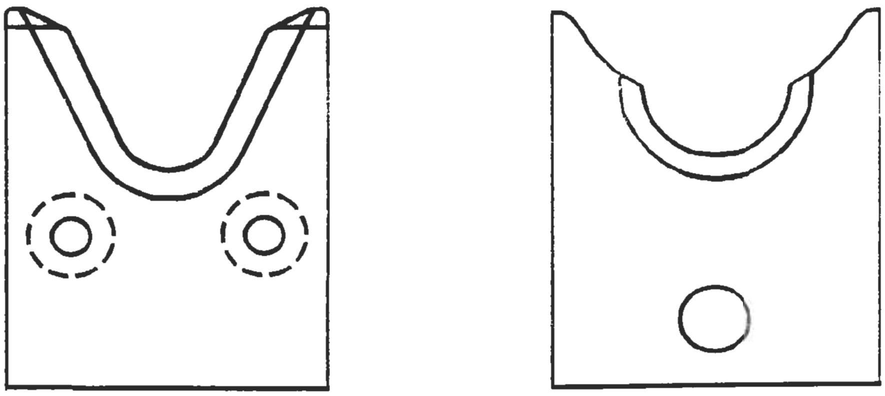
Table 1
RM vs Radius Type Shear Rams
Hydraulic System Pressures and Forces to Shear 70 Grade CT

Internal Pressure (psi)	CT Wall Thickness (in)	Hoop Stress (psi)	Upper Confidence Limit (99%) (cycles)	Lower Confidence Limit (99%) (cycles)	Life Prediction (cycles)
0	0.156	0	1,091	676	912
500	0.156	1,683	1,335	274	906
1,500	0.156	5,049	892	627	892
1.050	0.109	5,691	1,068	389	889
3.000	0.156	10.097	1.017	870	871

Table 2
Cycle Life Predictions from Life Prediction Model

Slip Mark Type	CT Wall Thickness (in)	Hoop Stress (psi)	Predicted Life for Unmarked (cycles)	Actual Life (cycles)	Life Reduction Due to Slip Mark (%)
Uninterrupted Teeth, Solid Slip	0.109	11,360	866	248	71.3%
Uninterrupted Teeth, Solid Slip	0.156	10,097	871	270	69.0%
Interrupted Teeth, Solid Slip	0.109	5,691	889	468	47.3%
Interrupted Teeth, Solid Slip	0.156	10,097	871	602	30.8%
Interrupted Teeth, Segmented Slip	0.109	0	912	488	46.5%
Interrupted Teeth, Segmented Slip	0.156	10,097	871	480	44.9%

Table 3
Reduction in Cycle Life Due to Slip Marks



"V" POCKET BLADE

RADIUS POCKET BLADE

Figure 1
Shear Blade Types

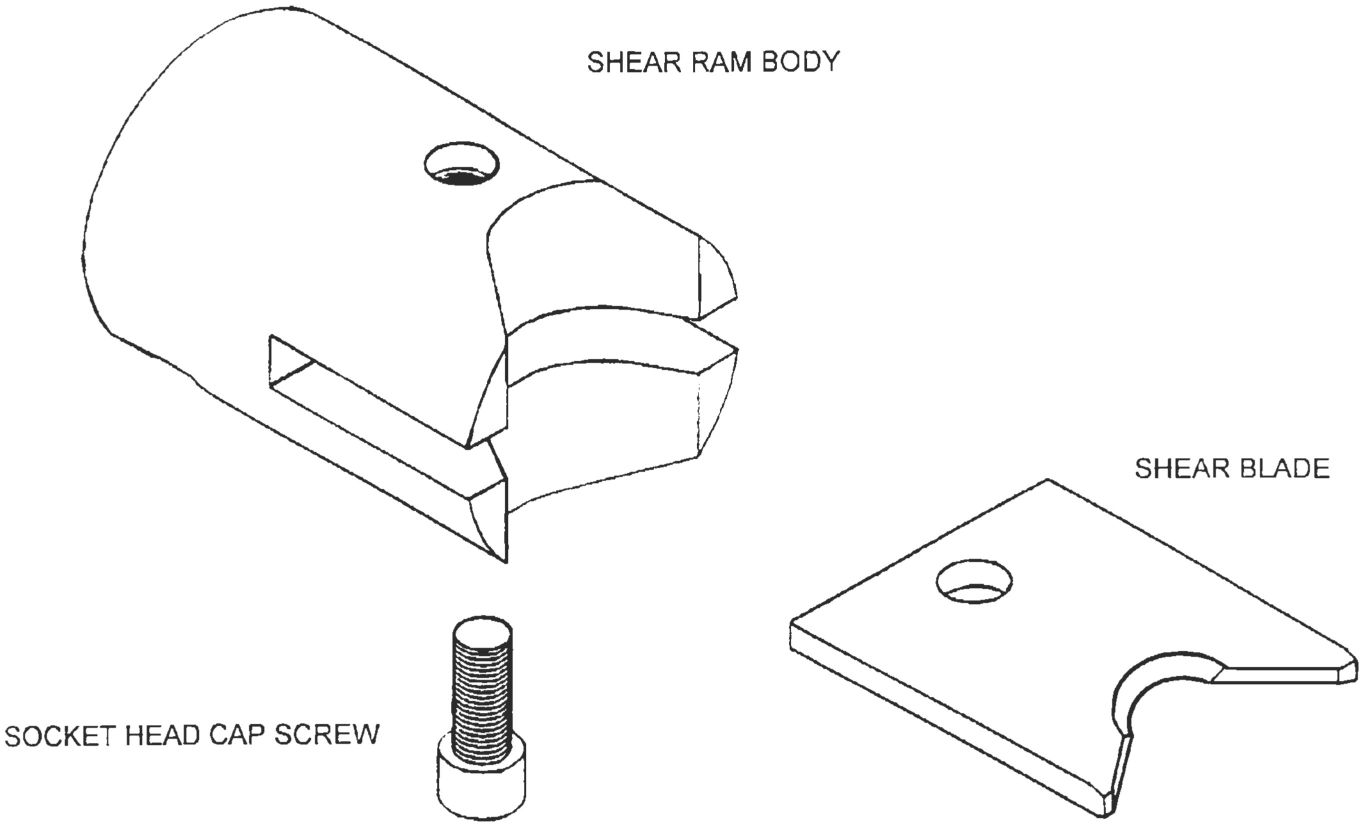


Figure 2
Shear Blade Ram Assembly

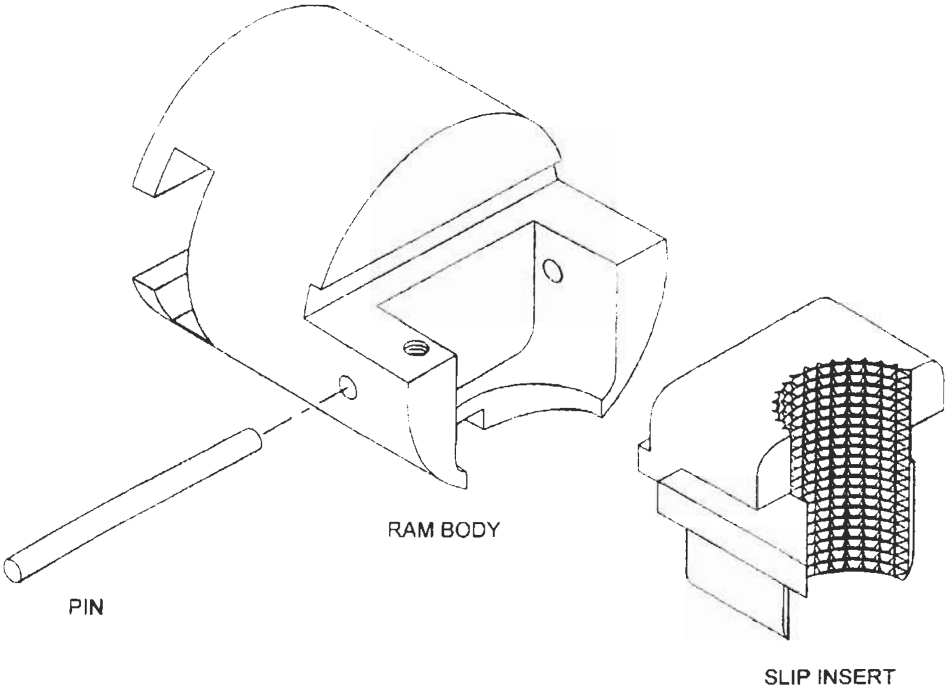


Figure 3
Extended Contact Slip Inserts with Interrupted Teeth

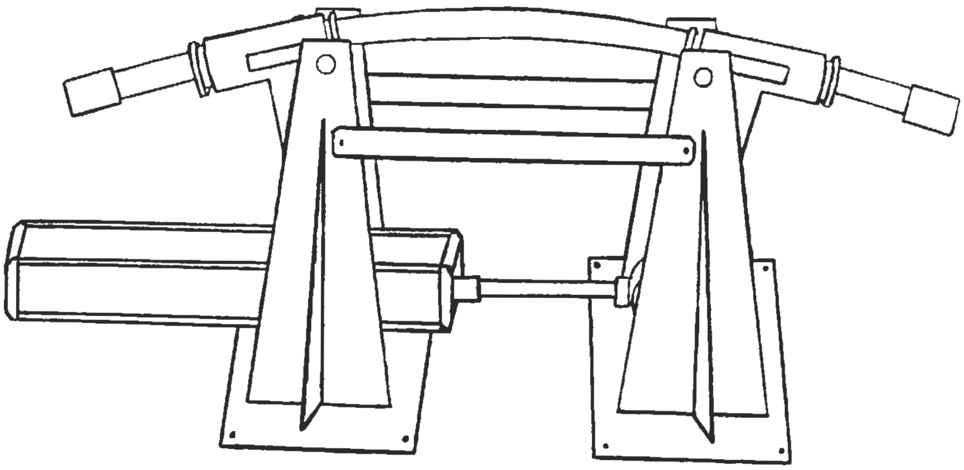


Figure 4
Four Point Bending Fatigue Test Machine