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# THE MECHANICS OF PIPELINE REELING

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ABSTRACT

The oldest method of submarine pipeline construction is to weld long lengths of pipe togheter onshore, to wind them onto a reel, to transport the reel to the site of the pipeline, and to unwind the pipe onto the seabed botton. The techniques required simply and particular advantage that is reduce the need for offshore operations close to the irreducible minimum. In practice, it has not achieved the degree of acceptance that might have been predicted. The reasons are partly technical, partly commercial and partly political. This chapter sets out to explore some of technical aspects of reeling.

## 1. The development of reeling Methods

In the last year of the Second World War, there was a need for pipelines from England to France to supply petrol to the allied armies. PLUTO was a bold and imaginative project to meet this need, by a fast and economical method which could continue in the face of war attack. 3 inch pipe was laind in 40 kilometre lenghts from floating reels (conundrums) 15 meters in diameter, toweved behind tugs and barges. Two types of pipe were used: one conventional pipe steel and other made by the same process as cable sheating. Although the pipe was bent some way beyound yeld, it was not strainghtened as it left the reel. Since the lines were expected to need for long, there was no corrosion protection system, and no be needed for long, there was no corrosion protection system, and no attempt to protect them against damage from fishing gear. Interesetingly, the PLUTO lines encountered some problems wich were later rediscovered by submarine pipeline engineers. At least one line collapsed by buckle propagation: that was cured by filling subquent lines with petrol before they were laid.

In 1961 Gurtler Hebet, a Luisiana contractor, converted a launding ship hull into a reel barge U303 (later RB1). It laid pipe up to 6 inches diameter from a vertical axis reel. The pipe was bent plastically in the horisontal plane, and had to be straightened before it was laid, since otherwise the suspended span would bow siderways and the pipe would form a series of kinks on the seabed. A second barge RB2 (later Chickasaw) was constructed in 19770 and again laid pipe from a vertical axis reel. The techology was aquired by Fluor and later by Santa Fe, who went on tu build the reel ship Apache (Figure 1), wich went into service in 1979. the original concept for the reel ship was more ambitious project that the wessel actually constructed wich has a horisontal axis reel ship with a hub diameter of 16,5 meters and outer diameter of 25 meters. The maximum pipe weight on the reel is approximately 1800 tonnes and the capacity is 22 kilometers of 10 inch pipe, and proportionately more for smaller diameter. The reel ship been used successfully to construct a number of pipelines in the North Sea and the Gulf of Mexico, while reels and strainghtenner systems intended for smaller pipe have been mounted on a number of vessels.

The above relates to steel pipe. Flexible pipe has followed a separate development path, and has invariably been laid from reels. Since flexible pipelines can be accept tight bending radius, handling and laying methodshave much in common with cable-laying. On the Flexservice I layvessel, for instance, the pipe is stored in badkets with an outside diameter of 15 meters.

## 2. Reeling Mechanism

Consider first the form taken up by a pipe as it wound onto a cylindrical reel. If the pipe had no flexural stiffness, and a negligible self-weight, it would take up the form shows in Figures 4 a, because that would imply a step change on bending moment at the point of contact between the pipe and the reel. Figure 4 b shows the configuration taken up by initialy strainght, weightless, linear elastic pipe with flexural rigidity *F*, reeled onto a drum of radius *R* under a tension *T*. the bending moment in the pipe on the drum must be F/R, the product of the flexural rigidity and the curvature 1/R. since the bending moment must be continuous at the contact point, the tension acting through the lever arm Δ (the offset between the contact point and the line of action of the tension) must generate this moment, and so the offset must be:

$$\Delta = \frac{F}{RT} \tag{1}$$

.

Figure 4.c indicates the distribution of curvature in the pipe, here and throughout the paper, the sign convention for curvature is that a pipe conforming to reel has positive curvature, and that negative curvature corresponds to reverse bending. The configuration of the pipe can be determined by integration of a simple equation relating curvature to offset from the line of action of T.

In the pipe is to take up the form shows in Figure 4.b, the offset must be F/RT. If the offset is smaller than F/RT, the pipe takes up the form shows in figure 4.d. It then touches the reel at one point C, and bends away on tge right hand side of the drum before coming back into contact some way further round. Geometry then implies that the maximum curvature occurs between C and D, and that is greater than the drum curvature 1/R. if the offset is greater than 1/R on the other hand, the shear force in the free span is of opposite sign abd the contact point moves until the moment t the contact is again F/R.

Most pipelines bend beyound the elastic range as they are wound onto a reel. Plastic yelds ocurs if:

$$r/R>Y/E \tag{2}$$

Where r is radius of the pipe, R is radius os the reel (most precisely, the radius from the reel centre to the pipe axis), Y is the yeld stress and E is the elastic modulus. To exemple for the pipe about 10,75 inch diameter, steel X 60 pipe will yeld if it is wound onto a reel of less that 70 meter radius (which any practical reel must be). When a pipeline is bend to plastically its moment curvature relation has the form shows in figure 5, in which the inset diagrams represent the form of the distribution of longitudinal stress over the pipe cross-section. As plastic yeld begins the curve bends over as a largeer fraction of the cross section yelds plastically and as strain hardening progresses in the yielded region. Ultimately a buckle forms on the compression side but this does not happen until a very large curvature has been reached particularly with the relatively large wall ticknesses usually used for reeled pipe. If the curvature is increased monotonically to certain level (point Jin figure 5) and then decreased the initial unloading is linear, through poit K to L, and then the unloading curve again bends round under the influence of reserved plastic strain and coninues towards Q whith progressive yeld in compression of regions which has previously yielded in tension. The moment curvature relation for continued reverse bending does not exactly coincide with the ration for the bending of undeformed pipe in the same direction, because of the ionfluence of the Bauchinger effect, which reduces the yeld stress in compression of material that earlier yielded in tension. If the direction of bending is again reversed, from state Q for instance, so that the curvature increases, the moment curvature relation first returns along a line parallel to the initial loading line OP and the again bends over as reversed deformation begins.

What has to happen if the pipe is to be restrainghtened after plastic bending? Figure 5 and figure 6 redraw. A strainght pipe has zero curvature and is represented by a point on the M axis, not necessarily whit zero moment.

***Figure 1.Apache ship reeling***

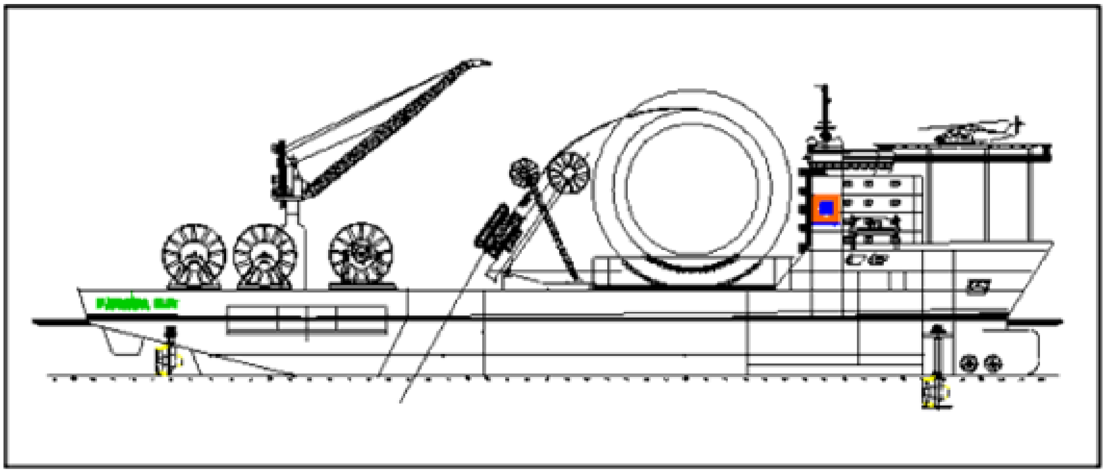

*Figure 2.Apache ship reeling methods*

The diagram shows a number of unloading paths which all lead to zero curvature. Only path PO leads to both zero residula curvature and zero residual moment, though not zero residual stress. Unloading from points on NP leaves a negative residual moment while unloading from points on PQ leaves a positive residual moment. If follows from thios argument that a pipe plastically bent on the reel and then laid on a flat seabed always has a residual bending moment unless its loading history is precisely OYJKLMNPO on figure 5 and that there are always residual longitudinal stressed which are tha same order as the yeld stress Y.

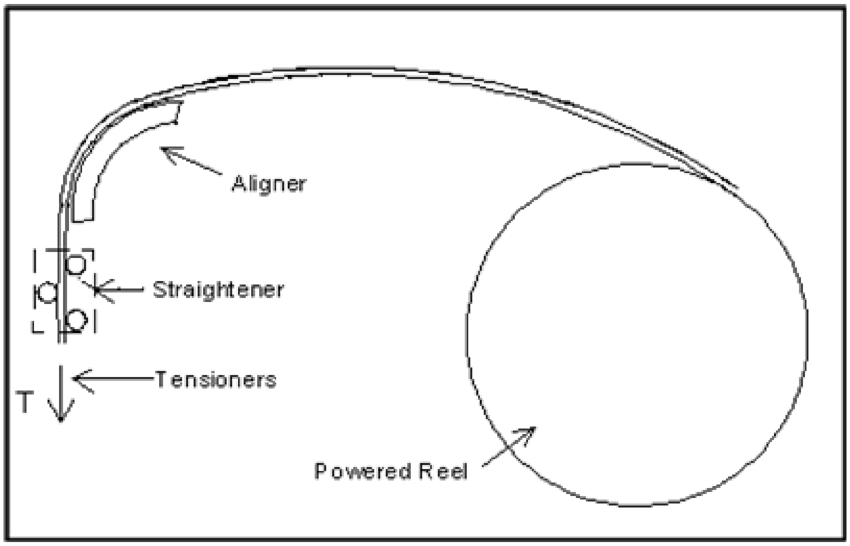

*Figure 3.Pipe reeling technology*

Concern is sometimes expressed about the influence of these stresses on subsequent behaviour in operation. How generates if the pipelines is subsequently hydro tested to a pressure which longitudinal stresses are at least partially erased. Hydrostatic testing has a major effect in reducing stress concentrations by localised plastic flow, and significantly lengthens fatique life. Pipeline designers less often make conscious use of the effects of hydrostatic testing but they are significant, for exemple reduced the very high residual stressed in cold bends and in generating favourable stress redistribution in spans.

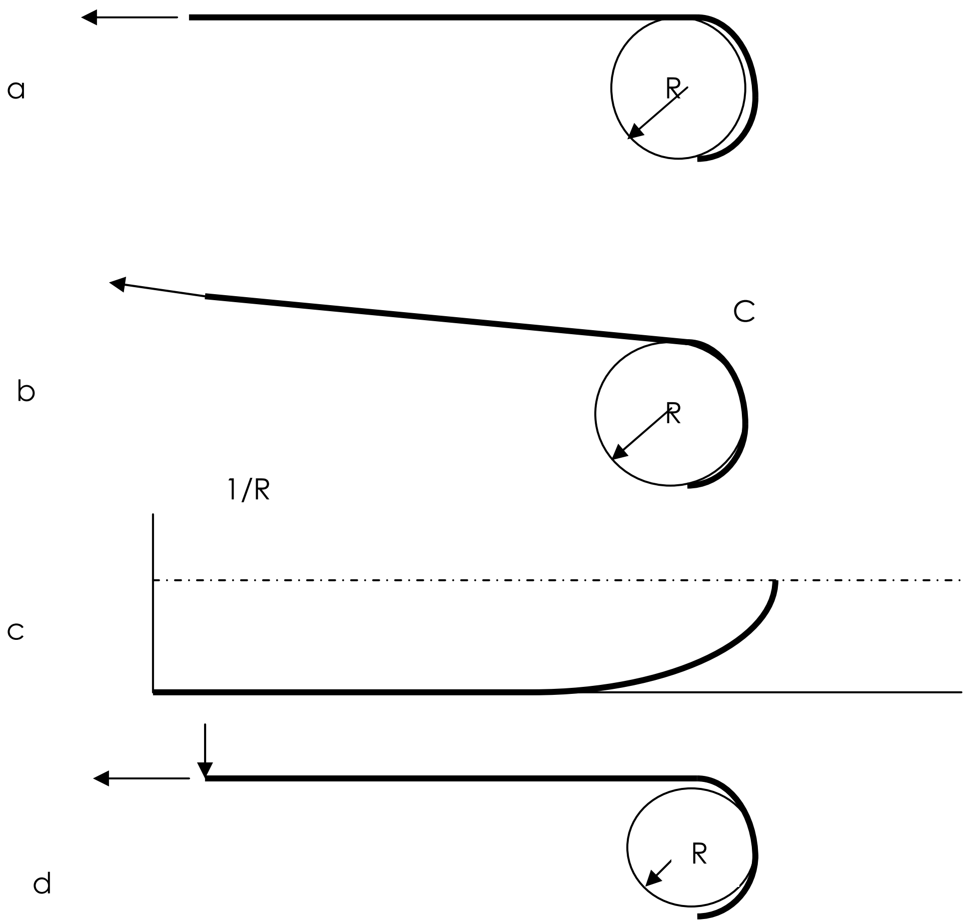

*Figure 4.The Effect of Rigidity on Pipeline Reeling*

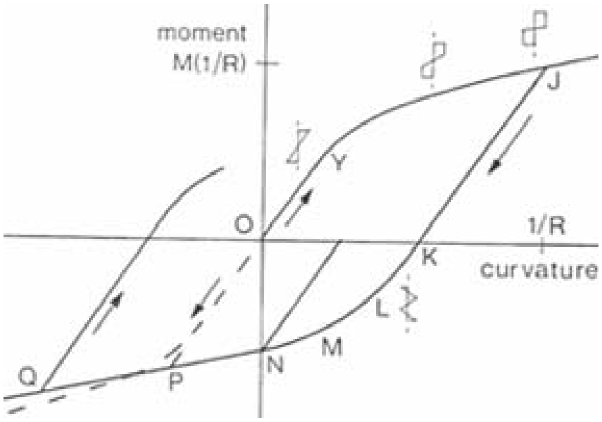

*Figure 5.Pipeline Reeling in the Plastic Regiune*

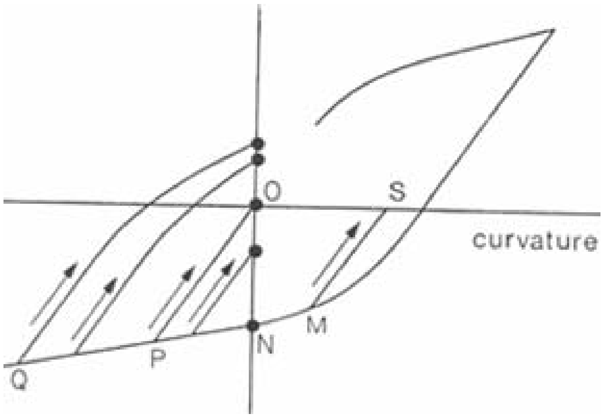

***Figure 6.The effects of Restraightening after Plastic Bending***

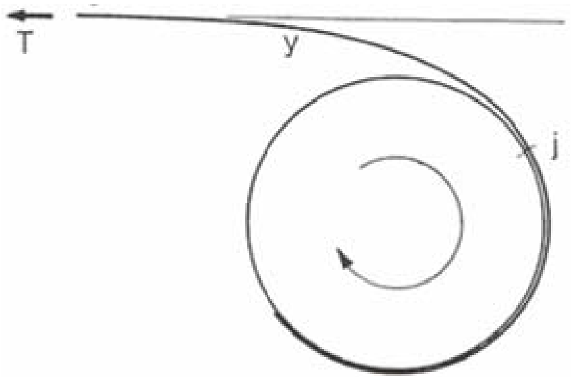

***Figure 7.Pipeline reeling under Tension in the Plastic Regime***

The moment curvature has important implications for reeliong and unreeling. Figura 7 shows a pipe bending reeled under tension T. the moment on the reel is M (1/R) and the offset must be (1/T) M (1/R). if the offset is less this, the pipe will bend away from the reel on the far side, as in the elastic case, and the maximum curvature and moment will be larger.

Unreeling is more complicated. Figure 8 shows a profile of the pipe as it is unreeled. The lowe case letters on the profile correspond to the points it is unreeled, the lowe case letters on the profile correspond to the points on the moment curvature diagram in Figure 5. at the point j at which the pipe loses contact with the reel, the moment is M (1/R) and the offset from the line of action of the tension is again (1/T) M ( 1/R). if any reverse plastic curvature is to occur the bending moment must be negative, and so the profile must lie above, the line of action of the tension force. At firest reverse plastic bending begins and at m the bending moment rechers its largest negative value. To the left of m the moment is small, and the pipe responds elastically with increasing positive curvature.

A profile of thid type cannot correspond to complete straightening which wouild return the state to point O in figure 5. as we have seen that would require a loading path OYJKLMNPO , and the largest negative moment coresponding to P, and simultaneosly the corresponding negativ curvature. At m in figure 7 however the moment is negative but the curvature must be positive. It follows that poit m in figure 7 is represented by a point on LN in figure 5. a subsequent reduction in bending moment will return the state along as unloading path from m, and the residual curvature at zero moment will be positive. In that sense, the pipe cannot be completely strainghtened by a unreeling process of the type shows in figure 7 in which the pipe is pulled from the reel by pure tension. Conventional reeling practice recognises this dificulty by passing the pipe through a straightening device after it leaves the reel.straighteners were introduced on the original vertical axis reel barges to avoid horisontal snaking that was found to occur if the pipe was laid with a residual horisontal plastic curvature. In its simplest form shows in figure 8 (overleaf) a strainghtener consist of three rollers which together induce a negative moment and curvature coresponding to point P in figure 5.

It is not essential that the strainghtening be perfect, thoung if it is not the pipe will have a residual moment after it is laid. That is whan happenens in floating reel laying without a straightener. A negative moment and concurret negative curvature is the siabed are generated by the weight of the pipe and the pipe is laid with a residual moment.

In some reeling aplications the process involved both flexure in the plane perpendicular to the reel axis and simultaneous lateral flexure in a traverse direction. The happens if reeling system does not traverse across the drum and straingtening then requires reverse bending in both directions.

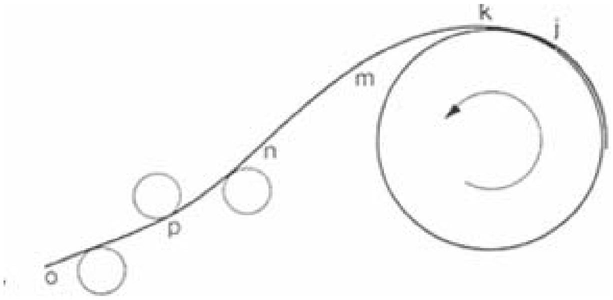

***Figure 8.Reel Pipe Straightener***

## 3. Pipeline ovalisation

Bending a pipe induces ovalisation into a roughly elliptical cross section, whith the minor axis of the ellipse in the plane of bending. Ovalisation is a nonlinear effect, and markedly increases in the plastic range. Excessive ovalisation is not acceptable, because of incompatibility with pigs and TFL tools. In Figure 9.a shows the longitudinal stress distribution in a tube bent beyound yeld and figure 9.b the forces on a short element. Since the ends of the element are not in line the longitudinal stressed distribution and both are necessary for the ovalisation to occur.

Consider now a pipe, as shown by Figure 9 ehich has been bent plastically to a positive curvature and then bent part of the way back so that the curvature is reduced. The interaction now generates forces which tend to flex the cross section back towards a circular form and indended to ovalised in the oposite direction. However as the curvature is futher reduced the effect weakens and when the pipe is again strainght there is no tendency to restore the circular cross section. When the curvature becomes negative interaction again tends to increase ovalisation in the original direction. The effect of these intereractions is that most of the ovalistation that occurs during bending is recovered during syraightening, but that some remains. Teste shows that the residula curvature is generally acceptable. If its is not futhere deovalisation can be achieved by the application of opposed external forces through rollers as part of a straingtening operation, though this requires relatively large loads which may threaten to damage the pipeline coating.

Experiments shows that in some materials reversed plastic deformation can reduce resistance to fracture. The effect is related to the growth of micro cavities and other defects which can initiate ductile crack propagation. However results of test on reeled pipe indicate that the effect is quite small at plastic strain levels reached during reeling and that can be taken care of proper specification of the pipeline steel.

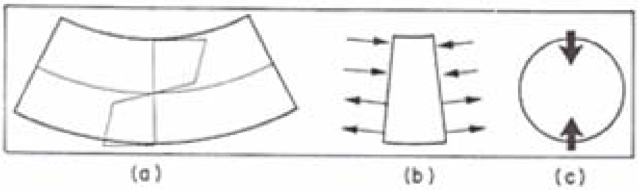

***Figure 9.The longitudinal Stress Distribution in a Tube Bent beyond Yeld***

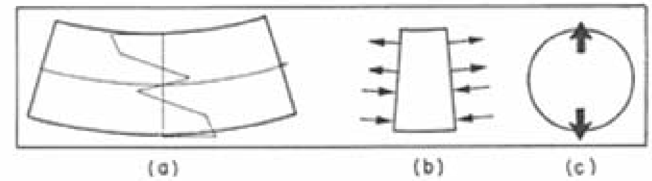

***Figure 10.The Longitudinal Stress due to Bending Reversal***

## 4. The problem with Anti-corrosion Coating

Submarine pipelines generally carry an external coatring of concrete, which protects the anti-corrosion coating against mechanical demage and gives the line enough weight for it be stable on the seabed. Conventional concrete coating cannot be reeled and so reled pipe has anticorrosion coating exposed to damange during reeling and straightening as it reaches the seabed and later during trenching and operation. More over inventional concrete coating cannot be reeled and so reeled pipe has its anti corrosion coating exposed to damange during reeling and straightening as it reaches the seabed and later during trenching and opertion. Moreover in order to give a reeled pipleine enough weight for stability its wall tickness has to be increased often beyound the level required by other design factors such as collapse and resistance to internal pressure.

This factor has important implication for reel constcuction because of its impact on project shedules. A decision to adopt reel has to be taken before the pipe is ordered. If as is much usual the shedule demands that pipe be ordered before construction tenders are received it may be too late to select reel construction whatever its other advantages.

The problem would be resolved by development of a reelable weight coating, not necessarily concrete. The last few years have significant progress in the development of tough and abrasion resistant protective coatings for submarinepipelines based on polymers and on polymer modified and fibre reinforced cement systems. This materials have so far been used as berrier coats to protect thin film coatings and in new filed joint systems but should wider applications. A reelable weight coating ought to be within reach.

## 5. Conclusion

Reeling is a extremely attractive methods of submarine pipeline construction. It transfer as many as possible of the oparation involved from the hight cost and wether sensitive environment offshore to a relatively low cost protected factory environment onshore. The pipeline can be carefully inspected and tested onshore, in conditions which allow time for thoughtful decision. Time offshore reduced close to a practical minimum abd the reel vessel can take advantage of brief wether windows and oportunities to work in congested around platforms. The full application of method has been delayed by concerns about the mechanical and metallurgical consequence of reversed palstic deformation and about coating damage. The fires concern seems to have been exaggerated and second os on the way to being solved.

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