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Shaft Strut Cavitation Problems

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ABSTRACT

In the 1880's, as a result of advancements in torpedo warfare, a new emphasis was placed on the speed of warships, particularly torpedo boats. At previously unheard-of speeds, certain weak links in ships' equipment manifested themselves. Among these weak links have been shaft strut cavitation and erosion. This paper outlines the historical background and describes cavitation problems associated with the shaft struts of selected contemporary destroyer-type ships. Causes and cures of the problems are addressed and recommendations furnished.

INTRODUCTION

Until the 1870's the cavitation problems of propeller shaft struts were not an issue in ship design. Briefly, cavitation is the flashing of water into vapor, caused by the dynamic pressure decreasing locally to less than the saturation pressure. This happens as the result of high-speed flow around a curved body. Early steamships were too slow to produce cavitating flow, and were usually single screw, with the shaft enclosed in the tapering afterbody of the ship. This type of stern has a minimum of curvature near the propeller and requires no struts.

In the course of the American Civil War, dramatic changes in naval technology became apparent. The introduction of so-called "torpedoes" - actually mines which could be moored in a harbor or carried at the end of a spar or towline - made it possible to sink a major warship with only one shot from a small, cheap "torpedo boat." The Confederate ironclad ALBEMARLE was sunk at her mooring by such an attack in 1864.

In 1866, the self-propelled torpedo was introduced by Sir Robert Whitehead. As it improved rapidly in speed and range, a torpedo attack on a battleship at sea became possible. To press home such an attack, however, the torpedo boat had to be fast. It had to endure the battleship's fire from the extreme range of the battleship's guns until the torpedo could be fired: and the torpedo's effective range was only 800 yards as late as 1900. This tactical situation produced a continual demand for more speed in the torpedo boats, to minimize their time under fire and to counter the target's evasive maneuvers as large ships used improving technology to increase their speed. In 1868 the fastest warship in the world, USS WAMPANOAG, made 17.78 knots on trials. (Even in 1853, sailing ships could go faster.) By 1877 a 27-ton torpedo boat could make over 19 knots. By 1890, a 105-ton torpedo boat could make 22.5 knots, and the authorities in Britain were so alarmed at this threat that they set out to design ships expressly to destroy the torpedo boats before they could close the increasingly vulnerable battleships. In 1893 the first "torpedo boat destroyers" were commissioned to implement this policy: they could all exceed 27 knots, and by the turn of the century destroyers had exceeded 35 knots.

This enormous increase in ship speed required dramatic changes to the technology used in torpedo boats and destroyers, and also called attention to the problem of cavitation. Torpedo boats switched from single to twin screws early in their development, and all early destroyers had twin screws with open shafts and struts. Struts were in common use in 1874 for twin screw ships. Propeller cavitation on a ship was first fully recorded as the cause of thrust breakdown on highly-loaded propellers for the British destroyer DARING in 1894. This was corrected by replacing the existing propellers with a set having more blade area. Cavitation was a problem for similar reasons for the fast-turning propellers on early direct-drive turbine-powered ships, starting with TURBINIA in 1897. The problem was solved in that case with three tandem propellers per shaft to divide up the thrust, and therefore the pressure differentials that were creating the cavitation.

DEVELOPMENT OF STRUT SECTIONS

Strut sections have varied over the years. At the turn of the century, strut sections were quite arbitrary. The shape used is not recorded. Undoubtedly, attention was paid to reducing resistance but apparently little attention was given to cavitation effects. It is of interest to trace the development of the more modern strut shapes.

In 1909, the U.S. Navy was using a low-drag streamlined strut section (first described in an unpublished table), having a chord-length to thickness (fineness) ratio of 7.5. The formula for this section (attributed to RADM David W. Taylor) was:

$$r = L \cos n\theta$$

where r = radius vector from the trailing edge
L = length of strut section
n = constant whose value was 8.4
θ = angle measured at trailing edge

whence one obtains in rectangular form (origin at trailing edge here):

$$x = L \cos n\theta \cos \theta$$
$$y = L \cos n\theta \sin \theta$$

This is the "Standard Strut Section" given in the 1912 and 1917 Bureau of Construction and Repair General Specifications (GenSpecs) for Building Vessels of the U.S. Navy, Section M-1 (Table 1). It had its maximum thickness at Station 7 (0.35 L), reckoned from the leading edge (or nose), and had a sharp trailing edge. The rationale for the use of this particular equation is not recorded. The Bureau of C&R customarily determined experimentally the direction of the stream lines in way of the struts with a view to minimizing resistance. However, many of the World War I "four piper" destroyers were built with struts aligned horizontally, or fore and aft, according to BUSHIPS Bulletin of Information No. 6 (reference 1), because the 1912 GenSpecs did not specifically require the struts to be aligned with the flow.

Service experience, unfortunately, indicated that strut arms having a fineness ratio of 7.5 were subject to "rapid corrosion". In the belief that a lower fineness ratio would be beneficial, about 1935, the Bureau of C&R started using strut sections having a fineness ratio of 6.0. This usage was formalized by a memorandum in 1941. Experimental work by the National Advisory Committee for Aeronautics, with a view to obtaining a reduction in resistance, cavitation and weight, supported this decision as the optimum compromise. At about the same time, the trailing edge was changed to a 1/8 inch radius. This is the "Standard Strut Section" given in the Bureau of Ships Design Data Sheet DDS 1108-1 for Shaft Struts, of 1 May 1947 (Table 1). This resulted in a change in the above formulas to read:

$$x = 0.8L \cos 8.4\theta \cos \theta \quad \text{or} \quad x = 1.0L \cos 8.4\theta \cos \theta$$
$$y = 1.0L \cos 8.4\theta \sin \theta \qquad\quad y = 1.25L \cos 8.4\theta \sin \theta$$

About 1950, the offsets were corrected slightly, as reflected in Mandel's paper on appendage design (reference 2) and given in Table 1 and Figure 1.

In the meantime, in the 1940's, the David Taylor Model Basin (TMB) developed a streamlined section which was designed for cavitation resistance at low angles of attack and low lift characteristics. This is the TMB-EPH (Ellipse, Parabola, Hyperbola) section, for which the formulas are, in dimensionless form:

Ellipse, for $0 \leq x \leq m$

$$y^2 = 1/4 \left[\frac{2x}{m} - \frac{x^2}{m^2}\right]$$

Parabola, for $m \leq x \leq 2m$

$$y = 1/4 \left[1 + \frac{2x}{m} - \frac{x^2}{m^2}\right]$$

Hyperbola, for $2m \leq x \leq 1$

$$y^2 = 1/16 \left[\frac{2x^2}{m^2} - \frac{12x}{m} + 17\right]$$

where: $x = \frac{X}{Y}$

$y = \frac{Y}{D}$

$m = \frac{M}{L} = \frac{2}{6-\sqrt{2}} = 0.436130$

L = Section length

D = Section thickness
X = Location from nose
Y = Section offset
M = Location of maximum thickness

This EPH section is given in the Bureau of Ships Design Data Sheet for Shaft Struts DDS 4301-2 of 5 Sep 1957 (now DDS 161-1 of 1 June 1982), and is currently in common use in the U.S. Navy (Table 2 and Figure 2). Unless exceptional transverse strength is needed, a fineness ratio (L/D) of 5.0 is used. In accordance with good design practice, fillets are normally required at the upper and lower ends of the struts where they meet the hull and the strut barrel, respectively.

It is of interest to note that, as early as 1907, in a paper on propeller struts (reference 3), Simpson showed, for both a freighter and a torpedo boat, strut sections of the general appearance of the EPH shape, but with a fairness ratio of 4. This presumably reflected British practice. That paper also noted that in "the old days of forged struts, solid elliptical sections were made.... with tail pieces in order to diminish resistance".

CAUSES OF STRUT DAMAGE

In recent years there has been a history of the struts having experienced deterioration damage. This is exhibited by the struts becoming pitted on their surfaces and by the development of notches in the strut trailing edges. This has been caused by cavitation erosion or corrosion, or both. In some cases, the cavitation generated at the struts has carried aft to cause deep pitting of the propeller blades near their hub.

As mentioned earlier, cavitation is the flashing of water into vapor resulting from the dynamic pressure decreasing locally to less than the saturation pressure. The dynamic pressure varies with the local speed of the flow, as described by the Bernoulli equation:

$$\frac{V^2}{2} + \frac{p}{\rho} + gz = \text{constant}$$

The local speed of the flow ("V" in the equation) increases dramatically as the fluid negotiates sharply curved surfaces, requiring a corresponding drop in pressure. In fact, potential flow airfoil theory predicts an infinite

velocity at the leading edge of a flat plate at an angle to the flow. Therefore it is at a sharp corner that the highest velocities, and thus the lowest pressures are attained. Should these pressures be less than the vapor pressure, a "cavity" of vapor will form, collapsing as soon as the local pressure recovers to a level greater than the vapor pressure (i.e., after flow has "turned the corner" and is negotiating a relatively flat surface).

Changing the attitude or the angle of attack changes the effective shape of the body, reckoned with reference to the undisturbed flow. This change in effective shape is almost violent if the body has a sharp leading edge, as on a thin flat plate set at a small yaw angle in a stream. Furthermore, as previously noted, cavitation can take place on a body where the pressure drops to the vapor pressure. This means that it can occur on a body if its shape or attitude is such as to establish cavitating conditions. Experience has shown that an elliptical nose tends to resist cavitation. This is the reason that the nose portion of a strut has an elliptical shape.

Thus, generation of cavitation can be due to improper shaping or fairness of the struts or due to their misalignment with the flow past the struts. In fabricating the struts, lack of attention to detail in their shape can result in the leading edge being cusped (spined) rather than rounded as is called for by the elliptical nose, so that cavitation is generated when an angle of attack occurs. Alternatively, the nose may be blunted, so that shoulders occur shortly aft of the leading edge; this results in a low pressure area which triggers cavitation.

Conventionally, struts are aligned with the flow, based on model tests in which pitot tubes or pivotable "flags" are placed where the struts are to be located. The angle assumed by these devices is determined and the struts aligned to suit, usually without spanwise twist. However, this measured flow angle may not be correct due to its having been determined without the presence of other appendages, such as the propeller shaft and strut barrel. The rotation of the shaft may also induce a change in flow angle. Also, the flow direction close to the hull (particularly in way of the intermediate struts) will differ due to the relative differences in thickness of the model and ship boundary layers. In addition, ship motions such as roll, pitch, yaw and heave can induce dynamic changes in the flow angle past the struts.

When the cavitation bubbles collapse against the strut, they exert very large local pressures which not only remove the paint coating, but also develop pits in the metal. These areas of bare metal are then subject to electrolytic corrosion, which can be accelerated by lack of cathodic protection in this region. If the stream of cavitation is sufficiently strong, the bubbles can be carried aft so as to impinge on the propeller, where their collapse can severely pit the propeller blades.

EXAMPLES OF CAVITATION EFFECTS

Guided Missile Destroyer Class. From the first, these ships' propellers eroded at an abnormal rate. Depending on the amount of high speed steaming, pits up to 1/2 inch deep could appear on the suction (forward) side of each blade about 6 inches out from the hub in less than a year after installation of a new propeller. Full-scale trials on one of the ships (Ship A) in 1965 revealed that a cavitation streak from the main struts was streaming aft onto the propeller. Subsequent strut alignment tests using pitot tubes suggested that the struts were misaligned near the hubs because they were of constant twist while the flow was not; the original tests had failed to show this accurately because the flow flags were too large to reveal differences in flow which took place over such tiny distances on the model. Realigning the struts was proposed as a cure for the problem, but the method - strut replacement - was rejected as too costly, and in 1964 the propellers were modified to unload blade sections close to the hub. This modification helped some of the ships.

Meanwhile, another ship (Ship B) developed a problem of strut erosion in addition to propeller erosion. The Charleston Naval Shipyard solved this problem in 1965 by installing a steel "wrapper plate" around the damaged strut, intending to protect it from further damage. Unexpectedly, the wrapper plate not only stopped strut erosion, but also reduced propeller erosion to an acceptable level.

More recently, NAVSEA's attention has been called to some of the still unrepaired ships. Two of them (Ships C and D) have required extensive propeller repairs or replacements. On inspecting Ship C and photographs of Ship D in 1981, it was discovered that their struts were in a deplorable condition (Figure 3), being badly eroded and far from the designed section shape. Instructions were issued to repair the struts by welding and grinding. It is possible that, as in the case of Ship B, repair of the struts will stop the deterioration of the propellers.

The question as to what extent the erosion is caused by strut misalignment as compared with lack of smoothness has not been established. NAVSEA measured strut angles in 1981 on Ship A, which no longer has propeller problems and on Ship C which does. There was no significant difference in angles as built, but on Ship A struts were much closer to the designed EPH section. In addition to being badly eroded, the leading edges of the Ship C struts were very blunt with a hard "shoulder" on each side (Figure 4). On the other hand, traces of erosion and patterns of marine growth observed on both ships immediately after dry-docking suggested that the struts were also misaligned with respect to the flow, and therefore cavitating only on one side of each arm. A full scale test proposed in 1981 to measure inflow angles and observe cavitation on freshly repaired struts could have settled the question, but it was not carried out. Obviously, if smoothing the struts can stop propeller erosion on these ships there is no real need for realignment. A smooth strut is more tolerant of misalignment, and conversely a misaligned strut requires a smoother section shape in order to avoid cavitation. Of the ships inspected in 1981, those with the smoother struts had no propeller erosion problems.

<u>SEALAND SL-7 Container Ships (reference 4)</u>. In their early days, these ships experienced loss of the fiberglass propeller shaft fairwaters and propeller dunce caps resulting in a "cavitation pattern that words cannot describe". In addition, each propeller blade fillet had a 30-inch long by 6-inch wide by 2-inch deep trench which eroded at the rate of 3/4 inch in depth each week. During a transit of one of these ships through the clear waters of the Caribbean, scuba divers took underwater motion pictures of the stern region at full speed. These movies showed patches of cavitation at the base of both the main and intermediate struts. The shape of the lower forward

portion of the main struts (EPH shape) was modified by the installation of a "boot" consisting of fairing plates, which had the effect of shifting the nose centerline four degrees inboard from the flow angle determined from model tests. The movies and the erosion pattern on the shell immediately adjacent to the intermediate strut showed a flow differing nine degrees from the original design. Fairing pieces were added along virtually the entire section of the strut, lengthening the strut section and reorienting its angle to more closely realign it to the flow. These modifications are reported to have been successful in correcting the cavitation. The erosion of the propellers was attributed to lack of attention to detail in the quality of the finish of the fillets at the base of the blades. Thus a better finish was adopted for the leading edges of the blades near the roots and for the fillets. The authors of this paper suspect that the cavitation bubbles generated at the base of the struts may have contributed to the propeller blade root erosion noted.

<u>Guided Missile Cruiser Class</u> . In 1974 while an unrelated hydrodynamic problem was being investigated, one of the ships of this class had occasion to pass by scuba divers at high speed in the clear waters of the Bahamas. The underwater motion pictures taken by the scuba divers showed a region of cavitation near the base of the nose of the main struts. Later examination of these struts in drydock showed pitting of the surface of the struts and that the nose portion of the fillets was blunted. The nose of the straight section of the struts was cusped and the surface was not fair. The intermediate struts exhibited the same sort of cavitation effects. It is considered that much of the cavitation experienced was due to lack of attention to detail in grooming the nose of both types of struts. It is also possible that the intermediate struts may not have been aligned with the flow, despite their angle having been determined from model tests.

<u>ASW Destroyer Class</u>. These ships are also equipped with EPH-shaped struts. These too have exhibited some cavitation problems. Here again the leading edges show signs of cusps in some portions and blunt noses in others. Furthermore, one arm of each of the main struts has at its nose, a pair of fairing plates which cover a duct which leads down the strut. These plates are Vee-shaped with the Vee pointed forward. The point of this Vee has undergone such severe cavitation erosion that a diver's knife can be inserted in the slot eroded between the plates. This demonstrates the power of cavitation and the need to pay particular attention to its prevention. It is planned to replace these plates with an elliptical "false nose" which will then cover the ducts.

<u>Patrol Craft</u>. More recently, in 1983, two high-speed patrol craft have been viewed while in drydock after only a few months of operation. Cavitation had removed most of the paint coatings - primarily on the inboard side of the struts - and had pitted the nose region. On one of these ships, the trailing edge of the struts was severely notched (some of them as much as one inch deep), partly due to cavitation and partly due to the impressed current cathodic protection system having malfunctioned. These struts were designed to have the EPH shape. However, on examination, the nose of each strut was found to be cusped. This was the probable source of the cavitation. The nose of the struts have therefore been rounded by grinding to approximate their intended elliptical shape. In addition, they have been carefully coated with Belzona C metal (a metal-filled polymeric material) under controlled temperature conditions, before application of new paint coatings. It will be

interesting to receive feedback on their performance after a period of operation. From model tests it was decided to set the struts with varying twist. However, the paint coating damage is greater on the inboard side than on the outboard side of each of the struts; this implies that the trailing edge of the struts should have been slightly toed in to better align them with the flow.

CONCLUSION

In order to minimize the likelihood of cavitation on struts, model tests should be conducted to establish the angle at which to set the struts. If these tests show that appreciable twist is required near the strut barrel, consideration should be given to accommodating this twist so as to better align the struts to the flow. It is recommended that the first ship of a class be equipped with viewports located near the struts, and pitot tubes mounted just forward of the struts. Trials would then be conducted to observe any cavitation pattern on the struts, and to check inflow angles for comparison with model tests. This would provide a basis upon which modifications to the struts could be developed if they proved particularly vulnerable to erosion.

In any case, care should be taken to properly shape the struts. Cusped leading edges should not be permitted. Shoulders, such as frequently occur in the strut-to-barrel fillet should be avoided. In other words, care should be taken to provide an elliptical shape in the nose area. Care needs also to be taken to assure fairness of the strut section.

TABLE 1

STANDARD STRUT SECTIONS

Station (from nose)	1909 Table & 1912 M-1	DDS 1108-1 1947	(for both)	Corrected NSS	
	$\frac{Y}{L}$	$\frac{Y}{L}$	$\frac{Y}{Max\ Y}$	$\frac{Y}{L}$	$\frac{Y}{Max\ Y}$
1	0.03564	0.04455	0.5346	0.04461	0.5352
2	0.04806	0.06008	0.7209	0.06007	0.7278
3	0.05594	0.06993	0.8391	0.06984	0.8378
4	0.06116	0.07645	0.9174	0.07629	0.9153
5	0.06438	0.08048	0.9657	0.08039	0.9645
6	0.06614	0.08268	0.9921	0.08264	0.9915
7	0.06667	0.08333	1.0000	0.08335	1.0000
8	0.06620	0.08275	0.9930	0.08272	0.9924
9	0.06470	0.08088	0.9705	0.08090	0.9706
10	0.06250	0.07813	0.9375	0.07798	0.9356
11	0.05932	0.07415	0.8898	0.07406	0.8886
12	0.05534	0.06918	0.8300	0.06918	0.8300
13	0.05072	0.06340	0.7608	0.06342	0.7609
14	0.04540	0.05675	0.6810	0.05679	0.6813
15	0.03942	0.04928	0.5913	0.04932	0.5917
16	0.03280	0.04100	0.4920	0.04104	0.4924
17	0.02556	0.03195	0.3834	0.03916	0.3834
18	0.01762	0.02203	0.2643	0.02209	0.2650
19	0.00910	0.01138	0.1365	0.01143	0.1372
20	0	0	0	0	0
Nose	Radius	Radius			
10°	0.04822L	0.04920L			
20°	0.04430L	0.04695L			
40°	0.03730L	0.04240L			

TABLE 2

TMB-EPH Section

(Ellipse, Parabola, Hyperbola)

Station	Y/L	Y/D	Y/Max Y
0.25	0.0125	0.1188	0.2376
0.5	0.025	0.1669	0.3338
1.0	0.050	0.2325	0.4650
1.5	0.075	0.2804	0.5608
2.0	0.10	0.3186	0.6372
3.0	0.15	0.3774	0.7548
4.0	0.20	0.4204	0.8408
5.0	0.25	0.4522	0.9044
6.0	0.30	0.4750	0.9500
7.0	0.35	0.4901	0.9803
8.0	0.40	0.4983	0.9966
8.72	0.43613	0.5000	1.0000
10.0	0.50	0.4946	0.9892
12.0	0.60	0.4647	0.9294
14.0	0.70	0.4085	0.8170
16.0	0.80	0.3260	0.6520
17.44	0.872	0.2500	0.5000
18.0	0.90	0.2170	0.4340
19.0	0.95	0.1480	0.2960
19.5	0.975	0.1027	0.2054
20.0	1.00	0	0

Radius at nose: $R_0 = 0.5732\ D^2/L$

Radius at tail: $R_1 = 0.2027\ D^2/L$

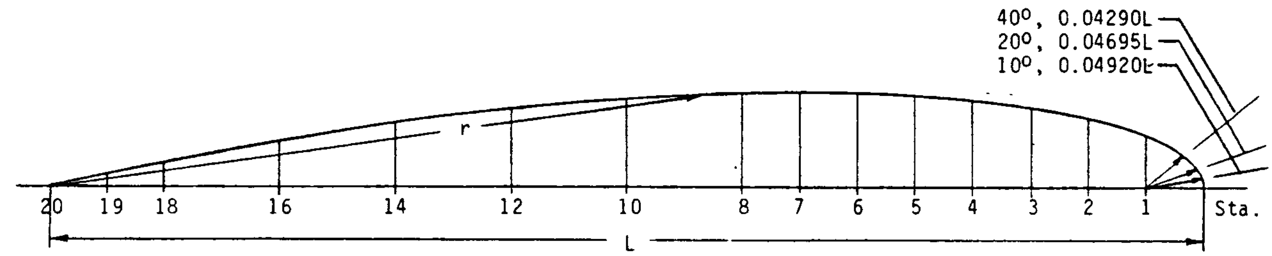


Figure 1
Navy Standard Strut Section (L/D=6)

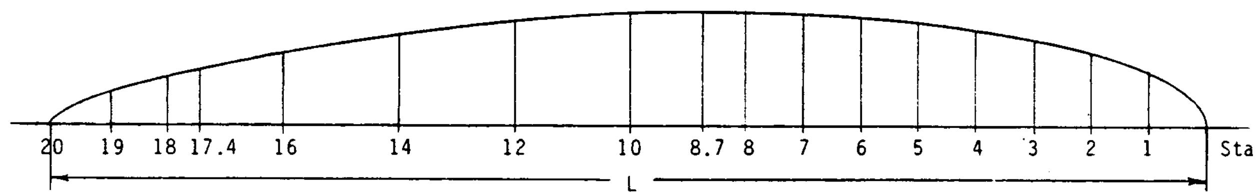


Figure 2
TMB-EPH Strut Section (L/D=5)

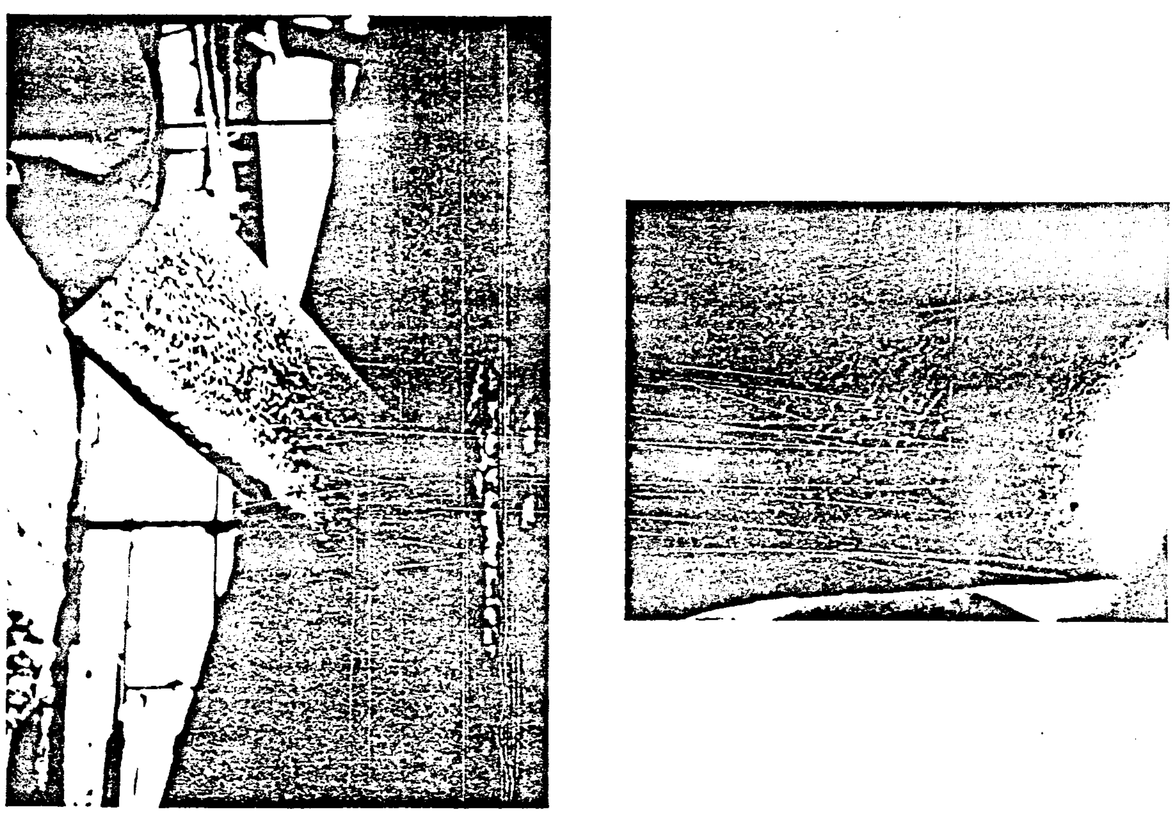
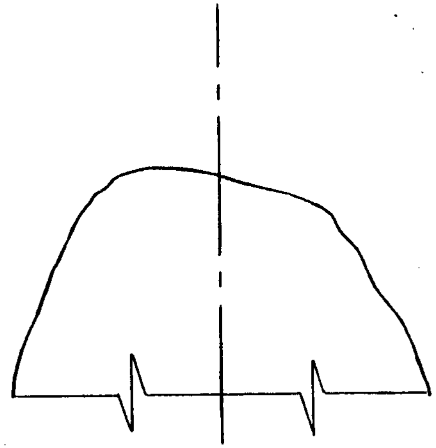
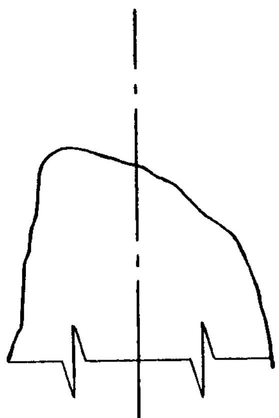


Figure 3
Typical Strut Erosion



4a. In way of strut-to-shaft barrel fillet



4b. In way of straight portion of strut

Figure 4

Typical Templated Strut Nose Section Shapes

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