A Very Simple Model of the distortion of light-weight ship structures

C.B. McKesson (AM)
P. Dong (V)

Ship designers are increasingly emphasizing the use of thin steel and light weight structure, including employing higher-strength steels to permit this scantling- and weight-reduction. These thin structures, however, present distortion-control challenges and too often the ship is delivered in a hungry-horse condition even when new. These problems are not necessarily the result of poor quality control. Instead, they are the necessary result of certain aspects of the physics of thin structure. It is our opinion that Naval architects do not, in general, understand the physics that gives rise to weld-induced distortion, and thus they make design choices that make such distortion nearly unavoidable. In this paper the authors wish to provide a Very Simple Model (VSM) which provides an effective high-level understanding of weld-induced stresses and their resulting distortions. This paper will not present a detailed and mathematical approach to weld modeling – this subject is left to welding specialists. Instead it our desire to raise the understanding of the naval architect or ship system engineer so that early stage design decisions can be made which will permit the ship builder to do the best possible job. It is our hope that this introduction will be simple enough to make a permanent contribution to the ship designer's understanding, and will reduce future frustrations, wasted effort, and production inefficiency.

KEY WORDS: Weld, Distortion, Lightweight structure, Design.

INTRODUCTION AND BACKGROUND

The authors have been proponents of Very Simple Models (VSMs) in several engineering applications. VSMs offer the ability to explore a problem rapidly and with a minimum of input, frequently saving many weeks of effort exploring fruitless corners of the solution space. Of course, VSMs are limited in fidelity and do not replace detailed design models. Instead, we view them as complementary, in the same way that a high-powered telescope is often fitted with a small spotting-scope which is used first.

In the present paper we wish to communicate a Very Simple Model of weld-induced distortion in shipbuilding structures. This model was developed by Dr. Pingsha Dong, and is one element of an upper-level course in Ship Production in the School of Naval Architecture and Marine Engineering at the University of New Orleans.

Dr. Dong's model utilizes a simple representation of a plate as a system of solid bars, each bar being heated or cooled in relation to its neighbors. A simple linear thermal distortion relationship is applied, and equilibrium laws are used to find the resulting stress and strain in each of the bars. The technique can be easily implemented via hand calculations, and despite its simplicity shows very good correlation with much more complex models.
Indeed, Dong's VSM of weld distortion is so easy to grasp that it often becomes a robust mental model, allowing an engineer to "feel" distortion patterns intuitively even before verifying them by calculation.

We wish to emphasize that this is not a new understanding of the physics of weld-induced distortion, rather it is attempt to reduce this physics to a very simple level. The physics of weld induced distortion is well known by welding engineers, but it is not well known by naval architects. One of us (McKesson) never encountered this in his 30 year career – admittedly one focused on concept design and not structural engineering. But many decisions that are made in concept design will have implications for production, and having this Very Simple Model of weld-induced stresses in mind will help the naval architect to conceive and develop a more producible ship.

THE THERMAL DISTORTION PROBLEM

The crux of the present Very Simple Model of weld-induced residual stresses and distortion lies in three basic insights, which will be developed further below. These are:

First: Weld-induced residual stresses are approximately equal to the yield strength of the material. This means that high-strength materials have higher residual stresses.

Second: Given then that the residual stress is approximately equal to the yield strength of the material, the second step is to realize that this stress will act in the same manner as an externally-imposed force upon the structure, and this force will result in deformation of the structure, in accordance with the laws of structural mechanics.

The magnitude of the 'imposed force' is simply the residual stress (in units of force per unit area) times the area subjected to this stress. Thus the third insight is that this stress-affected zone depends upon the characteristics of the weld, most importantly the size of the weld and the speed at which welding takes place.

THE VSM INTRODUCED:

Residual Stress is of Yield Magnitude

Consider a simple bar of metal, depicted in Figure 1. The bar is restrained by being placed between two immovable barriers, and the bar is then heated. Let us assume that the bar is steel, and therefore that the coefficient of thermal expansion may be taken as 6.5e-6 in/in/°F.

Let us assume that the bar has been heated to, say, 500F. At 500F the bar "wants" to grow 0.0033 in/in (0.325 percent) in length. But this growth is prohibited because of the fact that the bar is fixed between the endpoints. Instead, the bar is effectively compressed by these end supports, by an amount equal to the amount that it "wants" to grow – the free expansion amount.

At 500F the free expansion of a piece of steel is 0.00325 inches per inch of length. If this free expansion is prohibited, as by our end clamps, then this is exactly the same as imposing a compressive strain of 0.00325 in / in upon the 500-degree bar. Let us now consider what stress would result from a strain of this magnitude.

Steel has the simplified stress/strain relationship depicted in Figure 2. This is a simplified model in which the steel is assumed to be linearly elastic up to its yield point, and then to abruptly become perfectly plastic beyond this point. (This is the most common model of steel behavior, as taught in a typical engineering curriculum.) The yield strength of the material is designated Sy. The strain corresponding to this stress is Sy/E. For mild steel, with Sy=30 ksi, and E=30,000 ksi, the strain corresponding to yield is about 0.001 in/in.

Our bar of Figure 1 was heated to 500F, and experienced a strain of 0.00325 in / in. This strain well exceeds the elastic limit of the material, and will result in plastic deformation. In fact, from Figure 2, we can see that the bar will experience 0.001 in / in of elastic deformation, followed by an additional 0.00225 in / in of plastic deformation.

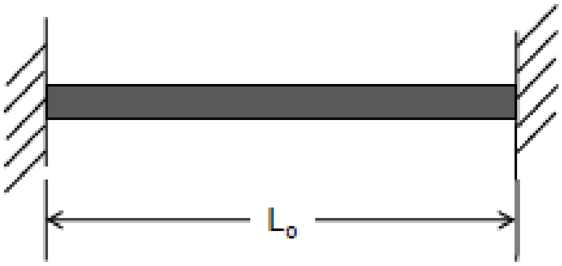

Fig. 1 - A steel bar restrained by two immovable end supports

Now what happens when the bar is cooled? The elastic deformation is recoverable – the bar will spring back by this amount when the force is removed. But the plastic deformation is permanent – the bar is permanently shortened by 0.00225 in / in. This means that when the bar is cooled, it will "want" to be 0.00225 in / in shorter than it was at the beginning of the heating cycle.

The first thing to notice is the degree to which the thermal strain has exceeded the yield strain of the material, despite the relatively low temperature under consideration. Real welds result in temperatures well above 500F across a substantial amount of material. And yet we see that, for this simple one-bar / fully-restrained case, any temperature above 154F will result in plastic deformation.

Let us pause again to consider this case: Heating the bar to 500F and then cooling it, is exactly the same as the following:

Imagine that we leave the bar at room temperature throughout. We compress it, as if in a vise, to a strain of 0.00325 in/in. We then release the vise. The bar will spring back by the amount of the elastic deformation (0.001 in/in), but it will be permanently shortened by 0.00225 in/in, whether we do this at room temperature by mechanical means, or mechanically fixed and driven by thermal means.

Now, up to this point we said that the bar "wants" to be 0.00225 in / in shorter in its cool state, than it was at the beginning of the experiment. But what if this contraction is impossible? What if the bar is incorporated into ship structure in such a manner that it is not free to shrink? Such a condition is sketched in Figure 3. In this case the bar, in the cold state, will be "stretched" by the restraining mechanism by exactly this same 0.00225 in / in amount. The bar "wants" to be 0.00225 in / in shorter, but it can't be – it is pulled by that amount. What is the stress due to this pull?

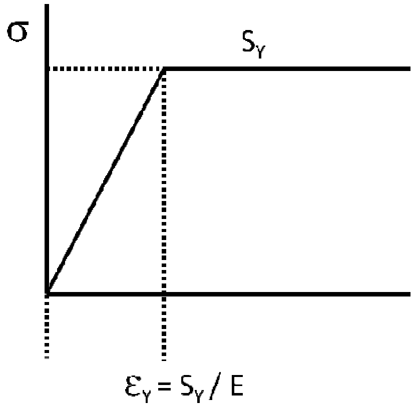

Fig. 2 - A simplified stress (σ) /strain (ε) curve for steel, assuming the material is linearly elastic up to yield, and then perfectly plastic above yield. Yield stress is denoted as Sy. The corresponding strain at yield isε y. E is the modulus of elasticity of the material

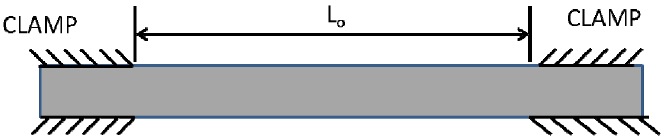

Fig. 3 The same bar as in Figure 1, but now clamped so that when cooled it can't shrink

Again, we can do this at room temperature with our vise: Glue the ends of the bar to the jaws of the vise. Now compress the bar as we did at first. It is elastically distorted .001 in/in and plastically distorted 0.00225 in/in in compression.

Now open the jaws of the vise to their original position. They are now pulling on the ends of the bar, pulling it back to its original length. What is the stress so induced?

Again consider Figure 2. Opening the jaws of the vise, the 0.001 in/in of elastic distortion "springs back," whereas the 0.00225 in/in of plastic distortion must be "pulled." Stretching the bar by 0.00225 in / in will again result in a new 0.001 in / in of elastic (spring-like) deformation (in tension now), and 0.00125 in / in of plastic deformation.

Given this then, with what force will the bar pull against its restraints? How hard is it pulling against the "glue" which holds it to the jaws of our vise? This is simple: It pulls with the force of the elastic deformation, which is to say with the full yield strength of the bar, and no more. The bar can't pull harder than yield, certainly.

This simple one-bar picture leads us to the first important conclusion from this VSM: Imagine that this 'bar' is actually a heat-affected zone in a ship structure. Perhaps it is a butt-weld of two plates. The 'restraint' is caused by the rigidity of the surrounding structure, and the result is that the weld is subjected to yield-magnitude tension, across the width of some heat affected zone.

Welding induces residual stresses that are, necessarily, of the same magnitude as the yield strength of the material.

Residual stress acts on an area driven by heat input

How hard did the bar, in our thought experiment above, press against the vise? We did all of the development in non-dimensional terms, in units of strain as inches-per-inch. To translate that to a real force we would obviously have to specify what the dimensions of the bar were.

In the case of this paper the "bar" represents an area of heated plate, due to welding. So the amount of force that this is going to generate will depend upon the size of the hot bar, which is to say it will depend upon the size of the heated zone of the weld.

The size of the heat input area is driven weld size

The size of the heated zone – and thus the size of the "hot bar" in our VSM – depends upon the size of the weld, and the amount of extra heat that the weld imparts to the surrounding metal.

Clearly the size of the weld has some relationship to the thickness of the metal being welded. But remember also that it only takes 154F to generate yield-magnitude stresses in steel. In any given weld it is extremely likely that the area that is raised to >154F will be much larger than the area that is actually "molten" by the weld.

However, this extra heat affected region can be reduced by welding fast, or by welding with technologies that accomplish their task with minimal thermal inputs – such as laser welding, friction stir welding, etc. Indeed, for the naval architect this VSM of weld distortion will be a sufficient introduction to explain a lot of the attractiveness of these high tech welding techniques.

APPLYING THIS VSM

Let us now consider what this VSM tells us about some realistic ship structural assemblies: A butt-weld and a T-Joint.

Application of the VSM to A Center-Heated Plate

Let us now apply this VSM to a realistic ship structural element. A butt-weld between two plates is basically the same as heating a narrow strip down the middle of a plate – Figure 4. There are two axes of interest in this case: across the weld (y axis) and along the weld (x-axis).

The across-the-weld case is simple, because we have already solved it: A slice across the weld in the y-direction is analogous to Figure 3, where "L" is the heated region of the weld, and the role of the clamps in Figure 3 is played by the two large expanses of unheated plate, which we will treat as immovable objects.

We already know the stress pattern in this case: After returning to room temperature the bar in Figure 3 is subject to yield-magnitude tension, imposed by the "vise". The butt weld in Figure 4 is subject to the same yield-magnitude tension in the direction across the weld.

If we now add more force, say by subjecting the butt-welded plate to hull girder loads, where will deformation first appear? It will occur where there is already a load right up to yield – it will occur as plastic stretching at the butt weld.

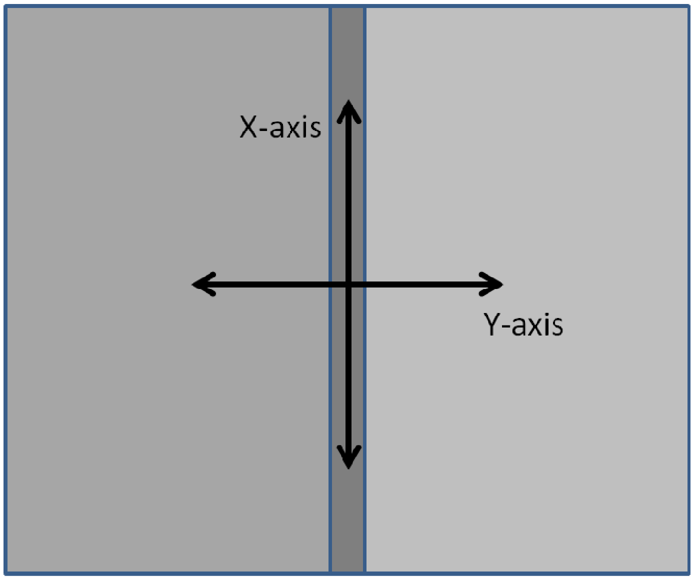

Fig. 4 - A butt weld (center) between two plates (sides)

What about the forces in the direction along the length of the weld? Here we have to add a small extra complexity because the "hot bar" is not perfectly clamped. In this case the VSM results in a 3-bar model as shown in Figure 5. Here the narrow hot bar is attached to two very large cold bars, via an infinitely stiff linkage at the end.

As we heat the center bar (the butt-weld strip) it "tries" to elongate just like the bar in Figure 1, but it is restrained by the two side bars. But just like too small a vise for the job, those two side bars can stretch a little bit, so they do permit the hot bar to grow a little bit. It's not enough to keep the hot bar out of the plastic region, but it might be enough to reduce the amount of plastic strain that is thermally induced. Also, depending on how big the cold bars are, we might end up with plastic elongation in them, where they have been stretched by the lengthening of the hot bar.

Of course, on cooling everything comes down and the signs and magnitudes change. The butt weld is now acting like a tight rubber band down the middle of the plate, pulling the plate in the x-direction. Depending on how big the rubber band is, and how spindly the side bars are, this might even pull hard enough to buckle the plate, as conceptually illustrated in Figure 6.

Application of the VSM to a T-Joint

There are many different components of ship structure that can be very clearly illuminated by application of the this VSM, but we feel that it will be sufficient to take only one last case, the case of a stiffener on a plate, in a T-joint.

Figure 7 illustrates a T-joint. Recall that the effect of heat input (i.e. welding) is to create a region in the metal where it is under tension – to create a "taut rubber band" in the structure. In the case of the T-joint in Figure 7 this taut rubber band can be clearly seen to acting to pull the T-joint out of its 90-degree angle. Other variations on this same distortion principle are illustrated in Figure 8

INFERENCES FROM THE VSM FOR A NAVAL ARCHITECT

What does this VSM imply for the ship designer? There are several simple lessons to take. These lessons are offered here not as a complete list but only to show the power of this VSM, so that the Naval Architect will be encouraged to consult this model on his own project.

First, notice that the residual stresses depend upon the degree of restraint of the structure. In the case of the hot bar held in a vise, it was the fact that the bar was restrained from free thermal expansion that gave rise to the plastic yield of the bar. Had the bar not been restrained, it would have freely expanded when hot, and then returned to its original dimension on cooling – and been stress-free throughout.

The role of fixity becomes important when joining different thicknesses of material too: a thin plate is highly restrained by being welded to a thick plate. This restraint "ensures" that a yield-magnitude stress is present in the weld affected zone of the thin plate.

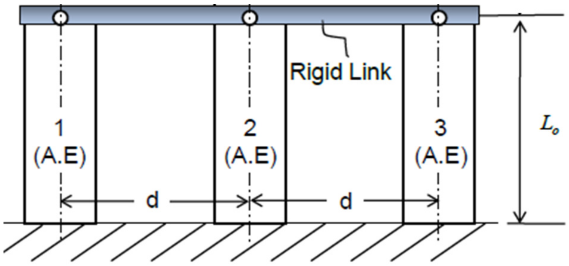

Fig. 5 - The VSM applied to the butt-welded plate, in the x-direction

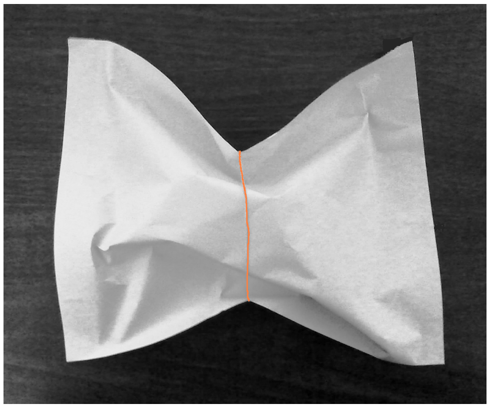

Fig 6 - The distortion of a butt-welded plate, illustrated by putting a rubber band on a sheet of paper

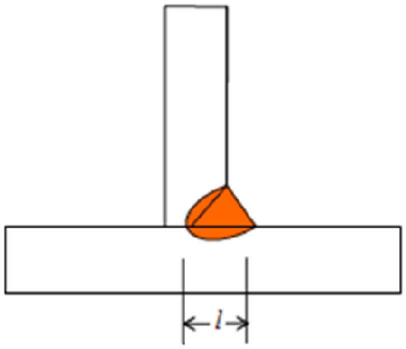

Fig. 7 - A T-joint, where the weld zone is acting to pull the T out of perpendicular.

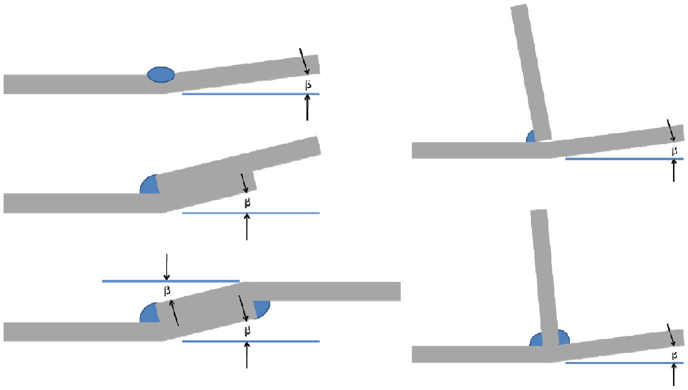

Fig. 8 - A textbook illustration of distortion modes due to welding analogous to the T-joint case

---

Because of this, consider the situation of an insert plate: Such a plate is highly restrained by the large expanse of surrounding structure. This means that the perimeter of the work will be a region of yield-magnitude residual stress, acting like an elastic waistband to the insert. This force will naturally lead to distortion of the hole, problems in fit-up of the insert. and distortion of the final assembly. This is not a defect in workmanship, it is a consequence of using an insert plate.

Note throughout that it IS possible for a good shipbuilder to build fair and attractive structures in thin high-strength steel. But doing so will require careful weld sequencing, weld design, and erection planning - all of which take time and money. Cost estimating algorithms that are based solely on steel weight will get this wrong – they will show a reduction in labor due to the reduction in weight attributable to using high-strength steel. The reality is the opposite.

Finally, consider the effect on part cutting. Even if we assume that the cut parts are stress-free and distortion free, the act of welding them together will introduce yield-magnitude stresses in the joints. How will these stresses deform the assembly? Will the deformations accumulate as assembles and built up? Will these result in later claims that the parts must have been cut wrong, because the assembly is out of true? There are myriad places that residual stresses can affect the ship structure. Much of this is well known by shipbuilders and their detail design staff. But the basics of weld-induced residual stresses are not often taught in naval architecture curricula, and it is this that we wanted to correct. We have presented a VSM of the physics of these stresses, in the hope that this can become a fundamental piece of knowledge in the Naval Architect's mind. Knowledge of the physics is a fine beginning to avoiding a host of problems downstream, and a good encouragement to listen attentively to the experts in the production planning.

CONCLUSIONS AND RECOMMENDATIONS

What have we seen?

- A piece of steel raised to welding temperatures will, if restrained, develop residual stresses that are of the same magnitude as the yield strength of the material.
- A butt-joint holds a yield-magnitude residual stress across the joint. It will be one of the earliest regions to distort when additional loads are added.
- A butt joint is a force to drive plate buckling in the direction along the weld. Again, this may not manifest until additional load is applied.
- These stresses are unavoidable results of the physics. A plate that is buckled by a butt joint does not indicate a bad weld – it indicates a lack of understanding of the forces driving plate buckling, and of the fact that a weld line *is* such a force.
- A T-joint imposes a force attempting to "hungry horse" a plate. Again, the same comment applies that it may take an additional load before the deformation becomes permanent (plastic.) Hungry horse is not a sign of bad welding, but of conceptual misunderstanding of the forces the plates are subjected to.

Hopefully, by embracing this very simple "A weld acts like a rubber band" model of thermally-induced residual stresses, the naval architect reader of this paper will be better equipped to design producible structures, leading to better shipbuilding, more efficient (and lower cost) fabrication, and happier customers.