Condenser Tube Buckling within Tube-Tubesheet Joints

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ABSTRACT

The problem of the appearance of protrusions, or bumps, in the interior of roller-expanded tubes within a tubesheet is addressed. Such bumps have been observed in condensers of power plants. A brief history of the reported occurrences of the bumps is given. The hypothesis is advanced that the mechanics of the formation of the bumps is similar to a buckling problem that has "bifurcation at infinity". Following this hypothesis, a two-dimensional physical model is developed, and the application of this model to study a three-dimensional bump is proposed. It is proposed in this paper that an initial deviation from the circular shape of the tube is required to produce a bump. It is shown that without such a deviation the tubes cannot buckle. An experiment with short tube segments has been performed that verifies some of the features of the observed condenser tube bumps. Exactly what force produced the initial deviation for the observed bumps is still unknown. Available evidence implicates the hydro-laser jet that is used in the cleaning of tubes and tubesheets. A scenario of how a bump could have been produced by the hydro-laser jet is proposed.

1. EVIDENCE

1.1. History of Observed Bumps

An investigation into the cause of the condenser tube "bumping" phenomenon was started early in 1988, after the discovery of these abnormalities in Susquehanna Steam Electric Station (SSES) condenser outlet-box tubesheet area. Upon inquiry, numerous reports of other incidences of bumps were noted. Inward buckling of tubes within the tubesheet, commonly described as bumps, had been reported at a number of locations: (1) SSES, Unit 1; (2) Montour; (3) Shoreham; (4) Point Beach; and (5) Clinch River.

A review of the various plant experiences showed that the phenomenon is: (1) not plant-specific; (2) not related to location; (3) independent of whether it is nuclear or fossil; (4) independent of any tube/tubesheet material combination; (5) not confined to a particular manufacturer of the equipment. A common thread among most, but not all, of the reported abnormalities was that a cleaning operation on the tubes or the tubesheet had been performed prior to the inspection which discovered the bumps.


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1.2. Metallurgical Findings

Fig. 1 shows the appearance of the condenser tube bumps, looking at them from the water box into the tube ends. They were confined to the section of the tube that is in contact with the tubesheet, and they project approximately 1/8 inch inward, toward the centerline of the tube. In these tubes, the bumps did not produce a leaking condition between the water in the water box and the condensate inside. However, some of the other utilities that were cited above did report leakage. Very similar photographs of tube bumps were received from the Point Beach plant in Wisconsin.

Fig. 2 shows the appearance of a bump from the outside of the tube after it had been removed from the tubesheet. Note that the bump is confined to the center of the tubesheet location and does not contact the inner and outer edge of the tubesheet. Good metal-to-metal contact between the tube and the tubesheet explains why leakage did not occur. Fig. 3 shows the cross section of the tube right through the bump.

1.3. Witness Report of Observed Bumps

As already mentioned in Subsection 1.1, the cleaning of the tubes has been implicated in the bumping process. A report of more direct evidence is also available. Ray Tombaugh from SSES witnessed the demonstration of some cleaning operations with a hydro-laser. Before the demonstration, the tubes appeared to be sound, with no bumps. After the demonstration, it was observed that some of the tubes had developed bumps, just like those at SSES. This observation provided a direct connection between the bumps and the hydro-lasing cleaning operation. Previous evidence had been always more circumstantial, because the bumps were found some time after someone recalled that a cleaning operation had been performed.

Available reports indicate that bumps in condenser tubes have been observed after they have been formed. However, no report is available that describes the actual process of the creation of a bump.

It must be emphasized here that the available evidence does not prove definitely that hydro-lasing produces bumps in condenser tubes. No eyewitness account is available of the actual process by which the bumps are created. Therefore, the precise cause of the bumps is still subject to debate. The objective of writing this paper is to provide information for such a debate.

2. Hypothesis for the Formation of the Bumps

The tubes of the SSES condenser, in which the bumps were found, had been expanded into the tubesheet by a mechanical roller. During this operation, the tube is pressed into the tubesheet by an expander up to a certain point and then the expander is withdrawn. The desired result of the operation is to leave a contact pressure between the tube and the tubesheet. The mechanics of this process has been described in a paper by Updike, Kahina, and Caldwell [1], in which a procedure is given for the estimation of the contact pressure. In a follow-up paper [2], it is shown that, depending on tube/tubesheet geometry and material, the contact pressure ranges from about 5-20% of the yield strength.
It is well known that a cylindrical tube, when subjected to external pressure, develops compressive membrane hoop stresses, which, if high enough, make the tube buckle to a deflected state. In an ordinary buckling problem of a cylindrical shell, which has a finite bifurcation point, the post-buckling deflections go both inward and outward. In the tube/tubesheet problem, however, the tube is constrained from deflecting outward by the tubesheet. If it becomes mechanically unstable, it can only buckle inward. This is similar to the situation of a ring that is compressed by a rigid, circular enclosure. Such problems are commonly referred to as buckling problems with “bifurcation at infinity”. The hypothesis is advanced in this paper is that the bumping of the tube is of this type.

3. MODELING OF THE BUMPING PROCESS

Having presented the evidence that bumps in condenser tubes do occur, research was undertaken to develop an approximate model that is simpler than the actual tube but can still capture the main features of the process by which bumps could form. Both experimental and theoretical evaluations of the approximate model were pursued.

3.1. Approximation

As seen from Fig. 2, the geometry of a bump is clearly three-dimensional, because the depth of the bump changes with the axial coordinate of the tube. The three-dimensional character of the problem complicates the study of the bumping process. Moreover, since the visible bump indicates permanent deformation, it is clear that the elastic limit in the material has been exceeded. Although the complete problem can be treated by a full-fledged elastic-plastic finite element model, it was decided that, as a first step, a two-dimensional model, for which the displacements take place in the plane that is perpendicular to the axis of the tube, could still model the main features of the process. Such an approximate model sacrifices the axial variation of the bump in favor of a more detailed investigation of the inelastic behavior of the tube. It amounts to the substitution of the tube by thin, unconnected circular rings. The deflection of the ring at the center of the bump corresponds to the maximum inward deflection of the tube.

3.2. Previous Results for Ring Buckling

If the representation of the tube by a ring is accepted, then the problem is the same as the buckling problem of a thin, elastic, circular ring, confined to a uniformly contracting boundary. This problem has been treated in the past. An important paper on this topic is by L. El-Bayoumy [3], where the elastic problem is treated in detail. The latest paper that has come to our attention is one by Techersch and Hueeater [4], where twelve references to other papers are given, the first one dated 1948.

The most important results obtained in these papers are that, if the contracting circular boundary is assumed rigid, then: (1) a perfectly circular, thin, elastic ring does not buckle at any contact pressure, which means that the only stable equilibrium state is the perfectly circular state; (2) buckling to a stable inwardly deflected shape can occur only if a finite deviation, with a certain depth, say δ, is introduced to the perfectly circular geometry; (3) the larger the contact pressure, the smaller δ is required for the ring to buckle to a stable inwardly deflected shape; (4) below a certain contact pressure, no magnitude of δ can make the ring buckle to a stable inwardly deflected shape.
These conclusions are valid for a thin ring, for which the elastic limit is not exceeded. This was the case in the experiments reported in [4], where the diameter-to-thickness ratio of the ring was about 500.

3. 3. Inelastic Behavior

It is clear from Fig. 2 that, for the SS3S condenser tube, the bump did not spring back and the tube did not return to its original, prebuckled shape. Thus, a permanent deformation of the tube has occurred, indicating that, in the process of the formation of the bump, the elastic limit of the material has been exceeded. This result could have been expected for thicker tubes, such as those used in the SS3S condenser. For this tube, the diameter-to-thickness ratio is about 60. Theoretical results that include plastic action are not available. To gain some insight to the plastic behavior, an experiment was performed.

3. 4. Ring Test

A number of rings, 0.5 inch wide, were cut from a 304 stainless steel tube, 1.0 inch O.D. and 0.024 inch thickness, which had approximately the same dimensions as the SS3S tube. The rings were placed between the upper and lower parts of the fixture, as shown in Fig. 4. The two parts of the fixture were constructed from a single piece of a 5/8 inch steel plate, with a hole, having a diameter of about 0.01 inch larger than the O.D. of the tube. The plate was then split into the upper and lower parts. The ring was inserted into the fixture, and the fixture placed in a 1000-lb-capacity Instron testing machine.

Before activating the machine, a pin of a selected diameter was inserted between the top of the ring and the circular hole of the upper part of the fixture. The pin produced the required deviation for the circular shape of the ring in order to make it buckle. The setup is similar to the model that is used in [4]. It is different because the all-around pressure was achieved in [4] by a hose clamp, while in our setup the pressure is applied through a displacement-controlled, relative motion of the two parts of the split fixture.

The total force applied by the testing machine to the fixture was measured versus the displacement, using the recorder connected to the testing machine. A typical load-displacement curve is shown in Fig. 5. At first the force is transmitted to the top of the ring through the pin to the bottom of the ring, where it contacts the lower part of the fixture. Thus, the ring is effectively loaded by two, diametrically opposed concentrated forces. The initial slope in Fig. 5 indicates elastic behavior (Region OA), which is followed plastic action, associated with the four-hinges mechanism (Region AB). This failure mode increases the horizontal diameter until it contacts the fixture. The new contact produces additional constraining forces that are responsible for the abrupt change in stiffness. Afterwards, the new contact zones spread along the ring (Region BC), causing a stiffening effect. Upon further loading, the geometry of the ring conforms more and more to the hole, which results in more stiffening (Region CD).

Eventually, the conformity is complete, except at the top of the ring, where it is disturbed by the presence of the pin. At this point, the transmission of the force is through both the hole surface and through the pin. The displacement imposed by the testing machine is increased until the pin can be withdrawn with no effort. This state corresponds to the maximum value of the load (point D in Fig. 5). The final state (Region DE) resembles a post-buckled state of the observed bumps in the condenser tubes. An important point is that at this stage plastic deformation can occur with a decreasing force.
3.5. Test Results

The main results of this experiment are summarized in Fig. 6, where the pin size is plotted versus the maximum load. Each cross marks the average of five tests, using the pin size indicated by the abscissa. The worst deviations from the mean of the five tests did not exceed 5%. Fig. 6 shows that for a smaller initial deviation (pin size), a higher load is required to reach a postbuckled state. It is believed that this curve follows closely the curve of hoop compression versus deflection for the condenser tube in its postbuckled state.

Images of the deformed rings are shown in Fig. 7. When the image of the deformed ring with a 1/8 dia. pin was enlarged and placed next to the shape of the buckled SSES tube that is shown in Fig. 3, the agreement between the shape of the buckled ring and cross section of the SSES tube was found to be remarkable.

3.6. Ring Test vs. Condenser Tube

The similarity between the pin and the tube is that they are made of the same material, have the same thickness and O.D., and are deformed to approximately the same shape. It is concluded that the simple model of a ring has captured some of the basic features of the buckling process.

In the experiment, it was shown that, when the pin was removed, the force that was needed to continue the deformation was decreasing but not zero (Region DE in Fig. 5), indicating that the continuation of the deformation process required work. We assume that this is so also in the condenser tube. In the test, the required work comes from the testing machine. In the condenser tube, the required work must come from the release of the elastic strain energy of the initial residual stresses. We note that in both cases the final state can be reached only after introducing a disturbance to the axisymmetry of the system.

3.7. Quantitative Evaluation of the Model

Fig. 3 shows the bump to be about 1/8 inch deep, including an angle of 40 degrees. According to Fig. 7, the 1/8 inch deflection matches approximately the pin size of 5/64 inch, and, from Fig. 5, the maximum load at that pin size is about 550 lbs. Assuming a uniform distribution of this load around the circumference of the ring and no friction, the contact pressure at buckling is roughly estimated as 550 divided by 1 inch diameter times 0.5 inch ring width, which gives 1100 psi as the average contact pressure. If friction is also considered, the contact pressure at buckling is expected to be lower.

This contact pressure is of the same order of magnitude as the one that could be expected after the rolling of the tube in the tubesheet. The expected contact pressure was obtained by the KshcITZ computer code which was described in [1]. For the tube/tubesheet dimensions and materials, KshcITZ predicted a contact pressure of 1200 psi. This quantitative comparison of the measured dimensions of the bump and the expected values lend credibility to the argument that the bumps were produced by a process that is similar to the plastic buckling of a ring in a uniformly contracting circular enclosure.
4. DISCUSSION

The question that still remains: what external action produced the initial deviation from the circular shape of the tube? A number of causes for the perturbation that results in the bumping of the tubes can be theorized. Among these are corrosion product buildup between the tube and tubesheet joint, manufacturing irregularities produced in the surface during fabrication, ovality of the tube after expansion, tube vibration between support plates, thermal-differential stresses, aggressive cleaning practices with high pressure water (hydro-lasing), material anisotropy, and the like.

Among these causes, aggressively applied hydro-lasing has been confirmed as being one of the possible causes of bumps in a laboratory test and has been directly implicated as having caused bumps in service at various utilities in the U.S.A. It is singled out here as the most likely cause of the bumps that were observed at SSES. Since a direct eyewitness account of the bumping process that is activated by the hydro-laser jet is not available, we present next a possible scenario.

5. PROPOSED SCENARIO

How could the bumps have been activated by the hydro-laser jet? Here is a scenario that is proposed in this paper.

As the hose of the hydro-laser equipment is pushed through the tube, the jet points backward to flush out the deposits. If the operator of the equipment is not careful, the head of the hose may be pushed out of the tube, in which case the jet could strike the sides of neighboring tubes, which protrude a small distance above the tubesheet. The jet, driven by a 10,000 psi hose pressure, produces a high enough force that deflects the edge of the tube inward. Momentarily, the top of the tube might look like the deformed rings shown in Fig. 7.

However, such an initial deviation from the circular shape could not produce the bump that is shown in Fig. 2, because the maximum depth of the bump is at the center of the tubesheet. It is postulated that further action by the jet creates enough pressure between the tube and the tubesheet so that the initial deviation at the edge moves further down, at least to the middle of the tubesheet. It is reasonable to assume that the contact pressure that has been left by the roller is higher at the center of the tubesheet than at the surfaces. This means that the depth of the deviation that has been introduced by the jet may be sufficient to make the tube buckle at the center but not at the surfaces at the tubesheet, as shown in Fig. 2. This means that, after the jet is withdrawn, the tube at the surfaces of the tubesheet springs back (again according to Fig. 2) to resume contact with the tubesheet, while at the center it remains in its post-buckled state. The result is the bump that is shown in Fig. 2.

It must be emphasized that this scenario has not been confirmed. Its weakness lies in the claim that a water jet exerts a sufficient force that can deflect a steel tube. Two observations lend support to the correctness of this claim. One is that the tube wall is rather thin (0.025 inches), and the other is that the velocity of the jet is very high. Of course, this claim could be subjected to a test. Such a test has not been as yet carried out.
6. CONCLUSIONS

This investigation has uncovered the following:


2. Theoretical solutions and experimental results of a physical model confirm all expectations and display no contradictions of the process of the formation of the bumps.

3. The physical model shows that initial deviations from the circular shape are required to make roller-expanded tubes buckle to a permanent bump.

4. After a cleaning operation by a hydro-laser there are bumps when before the operation there were no bumps.

5. A scenario exists by which the bumps can be produced by a hydro-laser jet.

What can be concluded? Mainly that the formation of the bumps is a buckling process, distinguished by "bifurcation at infinity", meaning that, at a finite load, a disturbance is required to produce a post-buckled state. Also, it can be concluded that the hydro-lasing operation is the likely actor that produced bumps in the SSES tubes. However, this has not been proved beyond the shadow of a doubt. In other situations, there may be other causes for the bumps. Finally, whenever an initial deviation from the circular shape of a roller-expanded tube exists, by whatever cause, the possibility of forming a bump will exist.

7. RECOMMENDATIONS

At SSES, directions have been given to the maintenance people that hydrolasing operations be confined strictly to the ID of the condenser tubes when needed to perform cleaning operations. At no time should the hydrolaser head be allowed to direct a water stream onto the outside of the tubesheet. For other heat exchangers, hydrolasing should be restricted and controlled so as to minimize impingement of the stream on the interface between the tube and the tubesheet.

If it is ever used for tubesheet cleaning, it is strongly suggested that a minimum of pressure be used to provide the cleaning action desired, that a fan spray pattern be used to disburse the liquid and that the tubes be inspected directly afterwards to determine the extent of any damage or buckling.

8. ACKNOWLEDGEMENT

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9. REFERENCES


Fig. 1. Condenser tube bumps observed at SSIS in January 1988.
Fig. 2. Condenser tube bumps after removal of tubesheet.

Fig. 3. Cross section of bumped tube at maximum depression.
Fig. 4. Test setup showing ring and fixture in the testing machine.

Fig. 5. Typical recorded load-deflection curve.
Fig. 6. Maximum measured force versus pin diameter.

Fig. 7. Final shapes of ring specimens.