Dynamic Studies of a PWR Steam Generator Tube Bundle

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Abstract
Tests have been performed on a reduced scale mock up of a steam generator tube bundle in order to validate a dynamic calculation model for seismic analysis. After presentation of the mock up, the main test results are given and the calculation model is detailed. A comparison is made on natural frequencies, mode shapes and loads on the support system.

1. Introduction
To qualify a calculation model for dynamic behaviour of PWR steam generator tube bundle, we must compare calculation and test results. So a mock up of a S.G. tube bundle has been defined and tests were carried out. Then a beam finite element model has been developed.

2. Tests
2.1 Experimental mock up
The mock up general scale was 1/3 and only 1/2 of the total height of tube bundle was represented: the 1/3 scaling ratio was specially used for the radius of the tube bundle, the tube and anti-vibration bar inertia and the masses.
But it was not possible to keep this ratio for the tube pitch and the number of tubes. Therefore, the steam generator 6,600 tubes have been represented by 232 equivalent steel rods (see figure 4).
The mock up consisted in:
- 232 steel rods with a diameter of 635 mm
- 1 tube sheet (diameter = 1.25 m)
- 8 tie-rods (diameter = 14 mm)
- 1 external shroud (for tests with water).
- 4 support plates
2.2 Tests Description
2.2.1 Shaker tests. The tube bundle in AIR or in water is excited by means of a small electrodynamic shaker fixed at the highest support plate to obtain the natural frequencies between 1 and 50 Hz and to measure the modes shapes. There were no links between the tube bundle and the shroud.
2.2.2 Seismic test-configuration without gap between support plate and shroud. The tube bundle and the shroud were fixed on a shaking table (3.1 x 3.8 m) moved horizontally by a 35 tons hydraulic actuator.
The mock up was tested in air and support plates were connected to the shroud by load-cells. Sinusoidal excitations were performed in the frequency range 1-45 Hz for different acceleration levels (from 0.1 g to 1 g) and also seismic signal excitations.

2.2.3 Seismic test-configuration with gap between tube support plates and shroud. A second series of tests was performed with 1 mm gap between the support plates and the shroud. These tests simulated a LOCA (Loss of Coolant Accident) excitation and a seismic motion.

The values of the impact load between the tube bundle and the shroud were measured with 8 loads cells located on the shroud at the level of the top support plate.

3. Calculation Model
A beam model of the tube bundle was defined with the following hypothesis:
- all tie rods have the same motion
- all tubes have the same motion
- tie rods are clamped on the support plates
- at the level of support plates the tubes have same horizontal displacements than support plates
- the support plates are rigid.

So the properties of the beam are:
- inertia momentum equal to the summation of the inertia momentum of all the tubes and tie rods; we consider two different values for in plane and out of plane motions
- section equal to the summation of tubes and tie rods sections.

On this beam, one must add:
- masses to represent the support plate masses
- rotational springs between the nodes located at the support plate level, which represent the stiffness of the connection of the tie rods on the rigid support plates (the rotation of the plates induces traction-compression axial forces on the tie rods and then momentum on the plates).

The boundary conditions are:
- tube bundle clamped at the bottom
- zero displacement of the nodes at the level of each support plate for the case without gap between tube bundle and shroud.

For each configuration, natural modes were calculated. Then, for configuration without gap between support plates and shroud linear calculation of the response was made.

For configuration with 1 mm gap, the response was obtained by non linear calculation using model superposition method and taking into account impacts; the modes are calculated with "free" boundary conditions at the impact locations.

4. Comparison between Experiments and Computation Results
4.1 Case of free support plate (shaker tests)
During sinusoidal tests, frequencies decrease with the excitation level and reach an asymptotic value, the frequency variation versus level is lower than 10%. For the first 3 modes, computation results and asymptotic experimental results are in good agreement (see Table 1). The influence of water on natural frequencies and damping ratios is small. This is
due to a large pitch diameter ratio (much larger than in a real steam generator).

4.2 All support plates fixed

4.2.1 Sinusoidal test. For this configuration with four fixed support plates several tests are performed with increasing acceleration (0.01 g to 0.2 g): as for the preceding tests, natural frequencies decrease when acceleration increases and reach an asymptotic value.

For out of plane motion, the calculated frequency is 14.35 Hz and the test frequency range between 14 Hz and 12.5 Hz (12.5 Hz is obtained for the highest acceleration level).

For inplane motion the calculated frequency is 32.3 Hz and the test frequency range between 39 Hz and 30 Hz.

Using a 7% out of plane and 15% in plane damping ratio, the calculated load on each support plate is compared to the measured load with an error varying from 10 to 27%. With these damping ratio the agreement is good for phases and for acceleration at the top of the mock up (see an example at figure 3).

4.2.2 Seismic motions. To calculate maximum loads and accelerations, the first mode response of the tube bundle is added to the static response of all the other modes by quadratic summation. This prediction technique gives values of the tube support plates loads with a precision of 30% in comparison with the measured values.

4.3 Test configuration with a 1 mm gap

Non linear calculation was performed to study the tube bundle response to a pipe rupture; the gap between the tube support plate and the shroud is equal to 1 mm.

The structure is projected against the shroud and then oscillates from one side to the other.

Table II gives a comparison between measured and calculated impact loads and also the instant of impact.

A fairly good agreement is obtained between calculation and load-cell results on one side, a 1 to 3 ratio is found on the other side.

5. Conclusion

All tests and computations are in good agreement for the configurations without gap between the tube support plate and the shroud. Therefore we can conclude that a simple beam model gives a good approximation of PWR steam generator tube bundle dynamic response.

For the configuration with gap between the tube support plate and the shroud, the non linear modal superposition method has been successfully used to obtain an estimation of the impact load on the tube bundle due to a simulated pipe rupture.
### TABLE I
Natural frequencies in Hz for the free tube bundle

<table>
<thead>
<tr>
<th>Mode</th>
<th>Axis out of plane</th>
<th>Axis in plane</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tests</td>
<td>Calculation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AIR</td>
<td>1</td>
<td>2.85</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>10.45</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>% 20</td>
</tr>
<tr>
<td>WATER</td>
<td>1</td>
<td>2.95</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>19.4</td>
</tr>
</tbody>
</table>

### TABLE II
Impact load in the test configuration representing LOCA

<table>
<thead>
<tr>
<th>Side</th>
<th>Calculation</th>
<th>Test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Instant of impact</td>
<td>Load in N</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>West</td>
<td>23 ms and 36 ms</td>
<td>10 000</td>
</tr>
<tr>
<td>Est</td>
<td>66 ms</td>
<td>29 330</td>
</tr>
<tr>
<td>West</td>
<td>135 ms</td>
<td>8 400</td>
</tr>
<tr>
<td>Est</td>
<td>155 ms</td>
<td>18 180</td>
</tr>
</tbody>
</table>
Figure 3

SINUSOIDAL TESTS

SEISMIC TESTS
Figure 4 - PWR steam generator tube bundle mock up without shroud.