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DESIGN EVALUATION OF A MAIN STEAM SPHERICAL HEADER USING FINITE ELEMENT ANALYSIS

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INTRODUCTION

Babcock was approached by a client who had to replace a main steam piping spherical header due to creep exhaustion of the material (see Figure 1 and Figure 2). This was the result of extended operation at high temperature and pressure, as shown in Table 1. The original design had been done for 100 khr of operation, yet the component was used safely in service for approximately 200 khr. The question naturally arose whether the design could be re-qualified for 200 khr.

Calculations according to the latest BS EN 13480 design code showed that the design could be used for 120 khr. The client requested that more detailed work be done to qualify the design for 200 khr, if possible. This option was favoured above thickening the component or using more exotic materials.

Given its suitability to the problem, Babcock decided to use the Design-by-analysis (DBA) methods of BS EN 13445 in conjunction with finite element analysis (FEA).

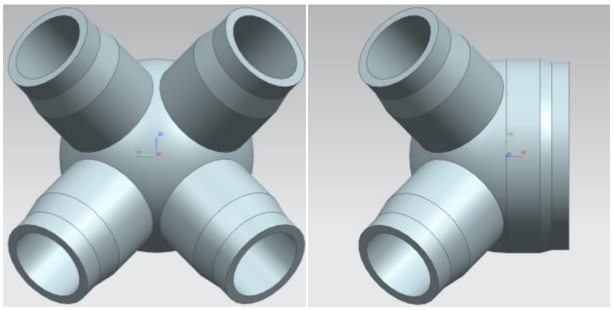

Figure 1: 3-D model of spherical header.

Table 1: Design data.

Parameter	Value
Design temperature	545 °C
Design pressure	18.5 MPa

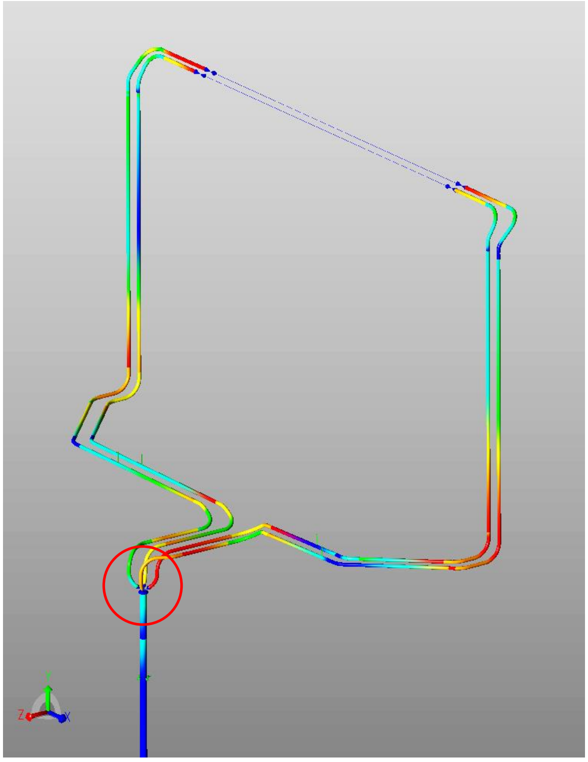

Figure 2: Location of spherical header in piping system.

OVERVIEW OF EN 13445 DBA METHODS

EN 13445 makes provision for the use of design-by-analysis, as opposed to the more commonly used "design-by-formula" approach in codes. DBA uses advanced structural analysis together with acceptance criteria specified by the code to assess the adequacy of a given design. This is done for all relevant failure modes of the component in question. In the case of the spherical header, the following failure modes are important:

- Gross plastic deformation (GPD).
- Progressive plastic deformation (PPD).
- Fatigue.
- Excessive creep strain (ECS).
- Creep rupture (CR).
- Creep-fatigue interaction (CFI).

The check for GPD is satisfied when the maximum principal structural strains (elastic + plastic) is less than 5% in a model with a linear elastic ideal plastic constitutive law and with partial safety factors applied to the yield stress and loads on the structure.

PPD of the component (commonly called ratcheting) is considered inconsequential if the maximum principal structural strains is less than 5% in a model after application of all cycles.

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Fatigue is checked using a conservative and simplified method given in EN 12952-3, which applies in the creep temperature range. Stress ranges are calculated from linear elastic analysis results and the familiar Miner's rule is used. Failure is conceded when $D_f \geq 1$.

Excessive creep strain is avoided when the creep damage indicator, calculated according to Robinson's rule, does not exceed unity: $D_c \leq 1$. It is important to note that rupture times are calculated using the *reference stress*, and not stresses from a linear elastic model. The reference stress takes into account stress redistribution and refers to the level of stress dictated by primary loads.

Creep rupture is avoided according to EN 13445 when the maximum principal structural strains (elastic + plastic) is less than 5% in a model with a linear elastic ideal plastic constitutive law and with partial safety factors applied to the yield stress and loads on the structure. Here the yield stress is set equal to the rupture strength of the material at temperature.

FINITE ELEMENT MODELLING

Convergence

When using FEA in design, it is most important to ensure mesh convergence. Since nonlinear FEA uses incremental or stepping methods to approximate the actual solution, there is the additional requirement to make sure that the convergence tolerance and stepping parameters lead to converged answers.

Mesh convergence was demonstrated by requiring convergence of (1) stresses in a linear elastic calculation and (2) plastic strains in a non-linear calculation where loads are increased proportionally. The mesh was refined systematically until the change in stresses and plastic strains were less than 5% (see Figure 3). It was then further demonstrated that successive refinements of convergence tolerance and time stepping did not influence results.

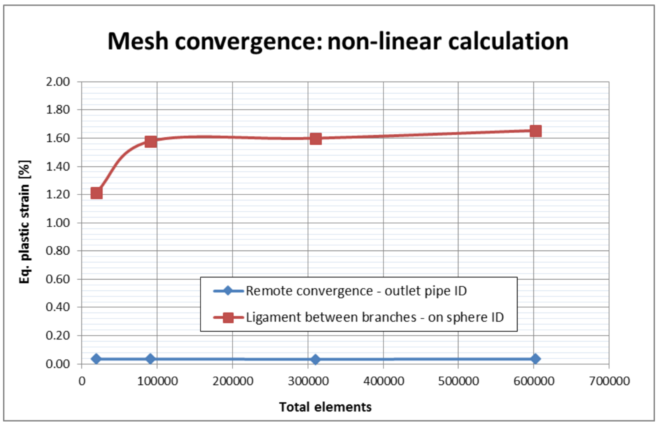

Figure 3: Convergence of plastic strains.

The spherical header was constrained at the extension pipe in the axial and tangential directions, thereby allowing only displacement in the radial direction. The branches were modelled similarly, except that the axial and tangential constraints were enforced via rigid multipoint constraints (MARC RBE2). The master nodes of the RBE2s were used to apply the pressure reaction force.

Pressure, with appropriate partial safety factors as specified for each individual design check, was applied on all internal faces. The directly proportional pressure reaction forces were applied on the master nodes of all RBE2s on the tube stubs.

Forces and moments caused by thermal expansion were applied to the branches of the header. These were calculated using a CAESAR pipework model.

Sanity checks

Firstly, it was checked that deformation of the component was sensible and that the boundary conditions had the desired effects. It was also checked that stresses (97.1 MPa) in the outlet pipe (large diameter) compared favourably with predictions from the Lamè formula (98.6 MPa).

DESIGN CHECKS

A summary of the design checks are shown in Table 2. The component failed the excessive creep strain and creep-fatigue interaction checks for 200 khr. The other checks were passed comfortably.

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Table 2: Summary of design checks (DCs).

Check ID	Allowed value	Model result	Check status
GPD-DC	$\varepsilon_{total} < 5\%$	$\varepsilon_{total} = 0.18\%$	PASS
PPD-DC	$\varepsilon_{total} < 5\%$	$\varepsilon_{total} = 0.015\%$	PASS
F-DC	$D_f < 1$	$D_f = 0.02$	PASS
CR-DC (200 khr.)	$\varepsilon_{total} < 5\%$	$\varepsilon_{total} = 1.08\%$	PASS
ECS-DC (200 khr.)	$D_c < 1$	$D_c = 1.41$	FAIL
CFI-DC (200 khr.)	$D_c + D_f < 1$	$D_c + D_f = 1.43$	FAIL

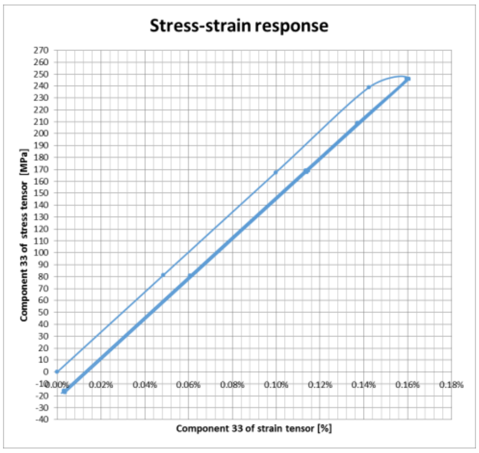

Figure 4: Shakedown of the spherical header after ±3 load cycles.

Figure 4 shows a graph of the stress-strain response of the branch ligaments. It is seen that the component undergoes shakedown to linear elastic behaviour following limited initial plastic deformation.

Fatigue damage was calculated according to the method of BS EN 12952, Annex B, since the fatigue clause in BS EN 13445 allows only for temperatures below 380 °C, which is not sufficient for creep components. The method is based on the maximum range of the principal stress differences and contains various corrections/factors applied to the stress range and to the S-N data. We have conservatively assumed that the components will encounter 2000 full pressure and temperature cycles during their life. Results from a linear elastic FEA, as shown in Figure 5, were used to obtain a stress range between cold and hot conditions. A fully corrected stress range of 574 MPa led to a damage rate estimation of 9.07×10^{-6} /cycle, thus giving a total of 0.02 after 2000 cycles. Therefore, fatigue is not a significant damage mechanism in the component.

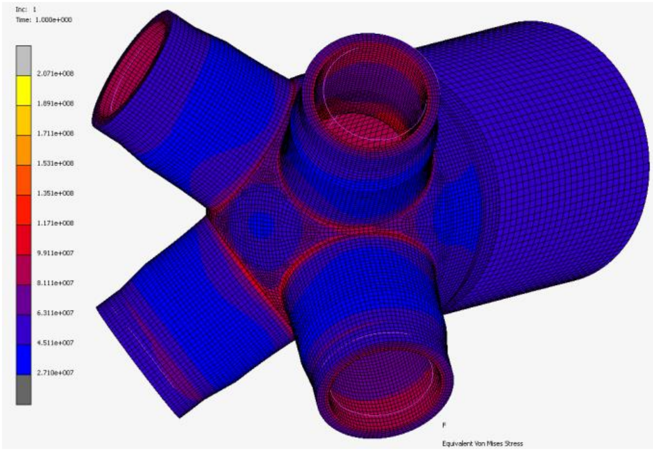

Figure 5: FEA results used for fatigue design check.

For 200 khr of operation at 545 °C, the component was found to fail the check for excessive creep strain and the check for creep-fatigue. However, note that a creep damage indicator of 1 would be achieved at approximately 142 khr, which is 22 khr more than the current design life.

Although the check for creep-fatigue interaction failed, we know that it is not a significant damage mechanism here, since the fatigue damage rate is almost negligible. It is rather a by-product of the simplistic nature of the check and the large value of the creep damage indicator.

CONCLUSION

Our client approached us with the need to re-qualify a spherical header for 200 khr of operation where current code formula design allows for 120 khr. It was demonstrated that the design is not suitable for 200 khr, but rather for 141.8 khr. This equates to roughly 3 years of additional operation at 80% plant availability. With the cost of the component at approximately R1.5 million, this is a significant life extension.