Design evaluations of high temperature piping system in sodium test facility

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1. Introduction

It is generally known that the design-by-rule (DBR) codes using simple formulae are more conservative than the design-by-analysis (DBA) code using a detailed finite element analysis [1]. Previous studies [2, 3] showed that B31.1 was more conservative for the mechanical loads while less conservative for thermal loads when compared with those of RD-3600 for a piping system in a sodium test facility. However, these studies were conducted using pipe elements which did not fully consider time dependent characteristics due to thermal loads.

In this study, the evaluation results from the DBR codes of ASME B31.1 [4] and RCC-MRx RD-3600 [5] were compared to those from the DBA code of RCC-MRx RB-3200 [6] to quantify the conservatism.

Integrity evaluations on IHTS (Intermediate Heat Transport System) hot leg of the STELLA-2 sodium test facility [7, 8] were conducted according to the design guidelines of DBR codes and DBA code. The DBR codes are the RCC-MRx RD-3600 of the nuclear grade French code for class 3 piping system and ASME B31.1 of industry design code on power piping, while the DBA code is RCC-MRx RB-3200 for class 1 nuclear components.

2. Analyses and evaluations

Design evaluations according to DBR codes were conducted using pipe elements, while those according to the DBA code were conducted with 3D solid elements. Two separate finite element analyses were conducted by ANSYS [9].

The analysis target is hot leg of IHTS piping system in the STELLA-2. The piping system has the hottest design and operating temperature in the STELLA-2 piping systems. Fig. 1 shows a 3D solid model of IHTS piping system in STELLA-2, the hot leg piping is shown in red color. The material of the hot leg piping is stainless steel 316L.

Fig. 2(a) shows a finite element model with 1D pipe element (pipe16) for DBR evaluation, and Fig. 2(b) shows a FE model with a 3D solid element (solid185) for DBA evaluation.

An IHTS piping system is subjected to high temperature and low pressure condition. Design data are summarized in table I. Finite element simulations under mechanical loads and thermal loads were conducted in the two separate models. Heat transfer analysis was conducted for design-by-analysis model.

As boundary conditions, built-in conditions were applied at the end of the piping systems for Fig. 2(a) model for DBR evaluations while radial direction was not restrained for Fig. 2(b) model for DBA evaluation with fixed boundary conditions for circumferential and axial direction.

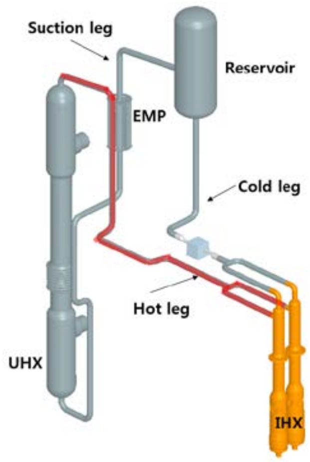
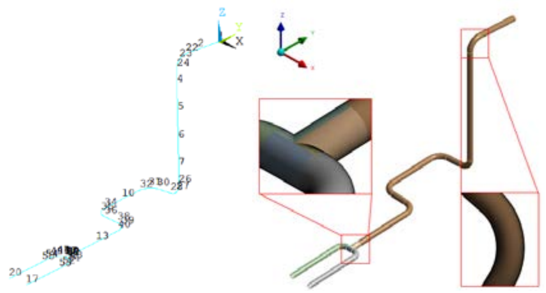


Fig. 1. An analysis target of IHTS hot leg piping (in red) in the STELLA-2 sodium test facility



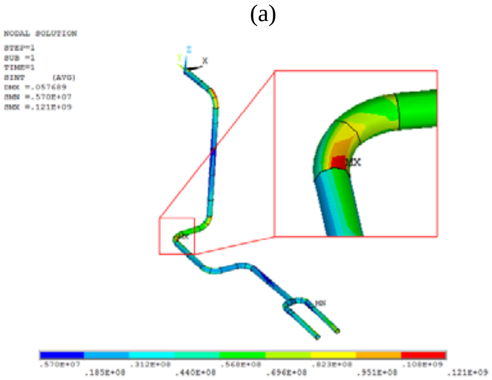
(a) (b)

Fig. 2. Finite element model based on (a) 1D pipe element (b) 3D solid element

Table I: Design data of the piping system

Parameter	Unit	Value	Remarks
Pipe OD / thickness	mm	114.3	4’’SCH20S
Pipe thickness	mm	4	
Design pressure	MPa	0.5	
Operating pressure	MPa	0.1	
Design temperature	°C	600	
Operating temperature	°C	550	
Total hold time : 75,000 hr Hold time: 150 hr/cycle, Design number of cycle : 500			

(a)



(b)

Fig. 3. S.I profile of pipe element model. (a) mechanical loads (b) thermal loads

The profiles of the stress intensity (S.I) under mechanical loads and thermal loads in pipe element analyses are shown in Fig. 3 (a) and (b), respectively. In Fig. 3 (a), maximum S.I of 30.7 MPa under mechanical loads occurred at the end of pipe (connected to UHX in Fig. 1) while under thermal loads, maximum S.I of 121 MPa occurred at elbow part as shown in Fig. 3 (b).

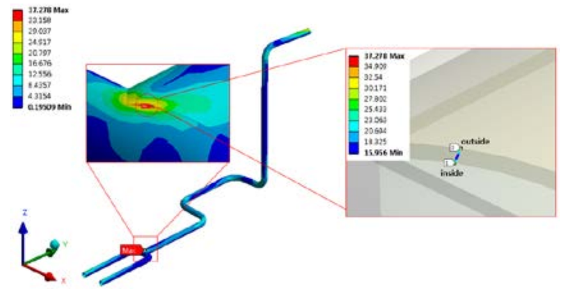
Table II and Table III shows evaluation results under mechanical loads and thermal loads, respectively. Table II and III show that B31.1 is more conservative than RD 3600 under mechanical loads while less conservative under thermal loads than RD-3600 except at the tee. In DBR evaluations, the trend is the same with the previous studies [2, 3] in terms of conservatism.

Table II: DBR evaluation results for mechanical loads

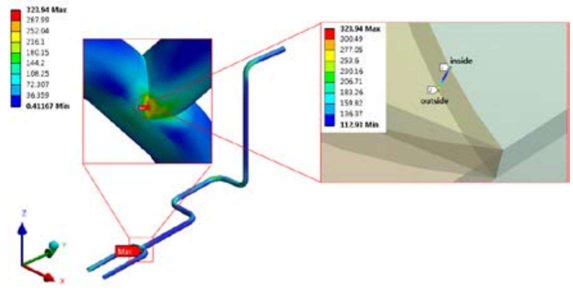
Node	Type	ASME B31.1		RCC-MRx RD-3600	
		Calculated	Ratio	Calculated	Ratio
1	Butt weld	42.7	0.74	40.7	0.55
40	Elbow	13.4	0.23	13.4	0.18
49	Tee	13.6	0.24	11.5	0.16
55	Reducer	6.6	0.11	6.6	0.09

Table III: DBR evaluation results for thermal loads

Node	Type	ASME B31.1		RCC-MRx RD-3600	
		Calculated	Ratio	Calculated	Ratio
20	Butt weld	113.8	0.58	107.8	0.61
30	Elbow	139.4	0.68	139.4	0.79
49	Tee	119.4	0.59	94.8	0.54
55	Reducer	33.2	0.16	33.2	0.19



(a)



(b)

Fig. 4. S.I profile and section for stress linearization of finite element model (a) mechanical loads (b) thermal loads

In case of DBA evaluation, Fig. 4(a) shows the profile of S.I under mechanical loads while Fig. 4(b) shows those under thermal loads. Each red box in Fig. 4 indicates section for stress linearization. Maximum S.I occurred at the tee part for both load cases. Maximum S.I of 37.3 MPa occurred at the top of tee part under mechanical loads, while 323.9 MPa occurred on the bottom of tee part under thermal loads. Each stress linearization was conducted according to RB-3200.

Table 4 summaries evaluation results according to DBA code. P_m, P_L and P_L plus P_b are related to mechanical loads and these ratio were lower than evaluated DBR codes (DBR: 0.74, 0.55 DBA: max 0.29) while under thermal loads, P_1 and P_2 are effective primary membrane stress intensity and effective primary stress intensity of the sum of primary stresses, respectively. As compared with DBR codes, RD-3600 was more conservative than RB-3200 (DBR: 0.68, 0.79 DBA: max 0.72). The other evaluation results according to the code requirements were shown to be within allowable limits as shown in Table IV.

Table IV: Evaluation results according to RB-3200 (DBA)

Evaluation items	Calculated	Limit	Ratio
$P_m < S_m$	17.71	77	0.23
$P_L < 1.5S_m$	17.71	115.5	0.15
$P_L + P_b < 1.5S_m$	33.899	115.5	0.29
$U(\Omega P_m)$	1.9756E-10	1	0.00
$U(P_m+P_b)$	3.4534E-7	1	0.00
$W(1.35P_m)$	5.4933E-6	1	0.00
$W[1.35(P_m+\Phi P_b)]$	0.0001	1	0.00
$P_1 < 1.3\ S_m$	72.46	100.1	0.72
$P_2 < 1.3 \times 1.5\ S_m$	100.24	150.15	0.67
$\varepsilon_{plastic} + \varepsilon_{creep}\ (1.25\ P_1) < 1\ \%$	0.2367	1	0.24
$\varepsilon_{plastic} + \varepsilon_{creep}\ (1.25\ P_3) < 2\ \%$	1.0385	2	0.52
Fatigue damage, V	0.0221	See Fig.5	-
Creep damage, W	0.5818		-

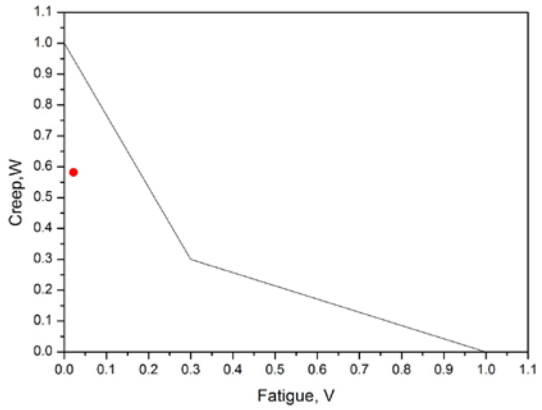


Fig. 5. Evaluated creep-fatigue damage by red dot on diagram

The evaluation result of creep-fatigue damage according to RB-3200 of RCC-MRx is shown in Fig. 5, which shows that evaluated creep-fatigue damage (red dot in Fig. 5) is within allowable limit. Also, it was shown that main damage was caused by creep rather than fatigue.

The evaluations according to DBR and DBA rule were conducted for an IHTS hot leg in STELLA-2 sodium test facility operating at low pressure and high temperature. The analysis results showed that the locations of maximum S.I for both analyses were different and the level of stresses were different as well. In terms of conservatism, it was shown that 3D finite element analysis based DBA code was less conservative that 1D based DBR codes as shown in Table II to IV. However, all the design evaluation results were shown to be within design allowables.

3. Conclusions

An IHTS hot leg of the STELLA-2 has been evaluated according to DBR codes of ASME B31.1 and RCC-MRx RD-3600, and DBA code of RCC-MRx RB-3200. Three sets of evaluation results for a hot leg piping were summarized and compared. Evaluation results in DBR analyses according to B31.1 and RD-3600 showed that RD-3600 was more conservative under thermal loads while less conservative under mechanical loads than B31.1, which is in agreement with previous study [2, 3]. When comparing evaluated DBR and DBA in terms of conservatism, DBA according to RB-3200 showed that it is less conservative than DBR codes according to B31.1 and RD-3600.

It should be noted that DBR codes of B31.1 and RD-3600 presently do not take creep and creep-fatigue interaction explicitly and they contain more conservatism. Therefore, it is recommended to apply the DBR codes first for simplified and straightforward evaluation of the piping systems subjected to high temperature operating conditions, and if the design allowables are exceeded as per the DBR analysis, DBA according to RB-3200 can be applied. If the results according to DBA are finally within the design allowables, their designs are judged to be acceptable even if they exceed design allowable in DBR code.

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