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Risks of non-conservative design according to ASME B31.1 for high-temperature piping subjected to long-term operation in the creep range

Hyeong-Yeon Lee[1] · Seok-Kwon Son[2] · Min-Gu Won[3] · Ji-Young Jeong[1]

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Abstract This study investigates the risks of non-conservative piping design according to ASME B31.1 for high-temperature piping subjected to long-term operation at high temperature in a creep regime based on a sensitivity analysis of the hold time. Design evaluations of high-temperature piping were conducted over a range of hold times in the creep regime according to ASME B31.1, which implicitly considers the creep effects, and the French high-temperature design code of the RCC-MRx, which explicitly considers the creep effects. Conservatisms were quantified among the codes in terms of the hold times. In the case of B31.1, the design evaluation results do not change depending on the hold time at high temperature, whereas in the case of RCC-MRx, they do. It was shown that the design limits of RCC-MRx were exceeded when the hold time exceeded certain values, whereas those of B31.1 were satisfied regardless of the hold times. Thus, the design evaluations according to B31.1 did not consistently yield conservative results and might lead to non-conservative results in the case of long-term operations in the creep range.

Keywords ASME B31.1 · Creep · Hold time · High-temperature piping · RCC-MRx · Sensitivity analysis

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✉ Hyeong-Yeon Lee
hylee@kaeri.re.kr

[1] Korea Atomic Energy Research Institute, 989-111 Daedeok-daero Daejeon, Republic of Korea

[2] National Fusion Research Institute, 169-148 Gwahak-Ro, Yuseong-gu, Daejeon, Republic of Korea

[3] School of Mechanical Engineering, Sungkyunkwan University, Soeburo, Suwon, Republic of Korea

1 Introduction

ASME B31.1 [1] provides requirements for a wide range of power piping operating at high and low temperatures in electric power generating stations, industrial plants, geothermal heating systems, district heating systems, and so on. It is possible for a designer to use the B31.1 code for a high-temperature piping design. Here, a high temperature is a temperature at which creep needs to be considered in the design such as 425 °C for austenitic stainless steel 316 and 370 °C for Mod.9Cr–1Mo steel (ASME Grade 91) [2].

Notably, in the case of high-temperature piping design as per ASME B31.1, the creep effects are implicitly considered through the allowable stresses [3] and the design evaluation results do not change depending on the hold time; thus, the evaluation results of B31.1 are the same regardless of the high-temperature operation time even within the creep range. Therefore, B31.1 might not be appropriate for long-term operation at high temperature in the creep range because it does not consistently yield conservative results.

Only a few studies have been completed on the creep or creep–fatigue interaction associated with the application of B31.1 to a high-temperature piping design. Because there is no quantitative evaluation procedure for creep damage in B31.1, creep life evaluations have been separately conducted after B31.1 evaluations using a Larson–Miller parameter [4] or API 579 equation along with API STD 530 creep rupture data [5].

The piping systems in ultra-supercritical (USC) thermal power plants and Generation IV (Gen. IV) nuclear reactor systems [6], such as a sodium-cooled fast reactor [7] and a very-high-temperature reactor [8] (VHTR), generally operate at a high or very high temperature in the creep regime. The ASME code for power piping, B31.1, is normally used for the design of high-temperature piping in USC plants and high-temperature industrial plants, whereas the design codes for high-temperature piping of HBB-3600 in ASME Section III Division 5 [2] (hereafter 'HBB-3600') and RB-3600 of RCC-MRx [9] (hereafter 'RB-3600') are used in nuclear reactors. Because HBB-3600 [2] is still in an incomplete state, RB-3600, which provides concrete design rules with explicit consideration of the creep and creep–fatigue interaction, is widely used for the design of nuclear grade high-temperature piping.

In this study, the two parts in RCC-MRx, that is, RB-3600 of RCC-MRx for piping design and RB-3200 of RCC-MRx (hereafter 'RB-3200') for pressure boundary component design, were applied as well for comparison to assess the variations in creep and creep–fatigue damage as the hold time at high temperature increases. By comparing the design evaluation results for various hold times among the three design rules of B31.1, RB-3600, and RB-3200, conservatism as well as sensitivity to hold times in the creep regime was investigated in this study.

In the case of elevated temperature design-by-analysis rules for the pressure boundary components, comparison studies of ASME Section III Division 5 Subsection HB (hereafter 'ASME-HB') and RCC-MRx have been conducted in previous studies [10–13]. In the present study, design evaluations according to RB-3200 and RB-3600 were conducted using the Web-based design evaluation program HITEP_RCC-MRx, which was developed for elevated temperature design evaluations according to RCC-MRx in a previous study [14]. 'HITEP' is an acronym for HIgh TEmperature design evaluation Program.

It is important for a designer to use a consistently conservative design rule in the interest of reliability and safety particularly for a piping system subjected to high-temperature operation conditions in the creep range. Because ASME B31.1 does not explicitly and systematically consider creep effects similar to ASME-HB or RCC-MRx, it requires more extensive and strict examinations such as performing a surface replication technique, metallography, and diametral measurements associated with creep swelling [1]. These examination methods are not generally employed for piping or a component that was designed with explicit consideration of the effects of creep and creep–fatigue interaction when compared to those of ASME-HB or RCC-MRx. In ASME B31.1, the evaluations of potential damage resulting from creep, creep–fatigue interaction, and accelerated creep damage are specified to be periodically conducted over high-priority creep damage areas, particularly on welded joints. The frequency of the examination should be based on previous evaluation results and industry experience; thus, the code assumes invaluable industry experience because it does not explicitly quantify the damage from creep and creep–fatigue interaction. Therefore, it would be important for a designer using B31.1 to compare the piping design results from B31.1 and those from RB-3200 and RB-3600 that explicitly consider creep effects to assess if B31.1 could consistently provide conservative results for piping subjected to high-temperature loading in the creep regime.

As for material of high-temperature piping, 316L stainless steel is widely used in high-temperature plants. Because ASME codes [2, 3] do not yet provide high-temperature material properties for 316L in the creep range and a high-temperature piping design rule (ASME HBB-3600 is incomplete), RCC-MRx was used in the present study because it provides high-temperature material properties of 316L in A3 [15] of RCC-MRx and RB-3600 provides concrete high-temperature piping design rules.

2 Design evaluation of high-temperature piping according to ASME B31.1

2.1 Main equations in ASME B31.1

There are three main equations actually governing the design of power piping associated with the three load cases of sustained, occasional, and displacement loads; they are briefly described in the following.

First, 'Stress Due to Sustained Loads', the effects of pressure, weight, and other sustained mechanical loads shall meet the requirements of Eq. (1) as follows:

$$S_L = \frac{PD_o}{(1000)4t_n} + \frac{0.75iM_A}{Z} \leq 1.0\,S_h, \quad (1)$$

where i is the stress intensification factor; the product $0.75i$ shall never be taken as less than 1.0; M_A is the resultant moment loading on the cross section due to weight and other sustained loads (mm-N); S_h is the basic material allowable stress at the maximum (hot) temperature; S_L is the sum of the longitudinal stresses due to pressure, weight, and other sustained loads; and Z is the section modulus (mm^3).

Second, 'Stress Due to Occasional Loads', the effects of pressure, weight, other sustained loads and occasional loads including earthquakes shall meet the requirements of Eq. (2) as follows:

$$\frac{PD_o}{(1000)4t_n} + \frac{0.75iM_A}{Z} + \frac{0.75iM_B}{Z} \leq kS_h, \quad (2)$$

where $k = 1.15$ for occasional loads acting for no more than 8 h at any one time and no more than 800 h/yr and $k = 1.2$ for occasional loads acting for no more than 1 h at any one time and no more than 8 h/yr and M_B is the resultant moment loading on the cross section due to occasional loads such as thrusts from relief/safety valve loads, pressure, flow transients, and earthquakes (mm-N).

Third, 'Stress Due to Displacement Load Ranges', the effects of thermal expansion and other cyclic loads shall meet the requirements of Eq. (3) as follows:

$$S_E = \frac{iM_C}{Z} \leq S_A, \quad (3)$$

where M_C is the resultant moment loading range on the cross section due to the reference displacement load range (mm-N).

$$S_A = f(1.25S_c + 1.25S_h - S_L), \quad (4)$$

where f is the cyclic stress range factor for the total number of equivalent reference displacement stress range cycles, N, determined using Eq. (5) as follows:

$$f = 6/N^{0.2} \leq 1.0. \quad (5)$$

N is the total number of equivalent reference displacement stress range cycles expected during the service life of the piping and S_C is the basic material allowable stress from Mandatory Appendix A of B31.1 at the minimum metal temperature expected during the reference stress range cycle.

As can be seen in the three aforementioned equations, fatigue is explicitly considered but creep effects are not but rather implicitly through the maximum allowable stresses which are described in detail in the next section.

2.2 Treatment of creep in ASME B31.1

The design code of ASME B31.1 is more commonly used for the design of low-temperature piping systems below the creep range. However, it is also widely used for the design of high-temperature piping of long-term and short-term operation within the creep range. Notably, the design evaluation results per B31.1 are the same regardless of the hold time in the creep regime because it does not explicitly consider creep effects. However, B31.1 states that accelerated creep damage leading to excessive creep strains and potential pipe rupture caused by extended operation shall be considered in selecting the design temperature for piping to be operated above 425 °C.

In B31.1, fatigue is explicitly considered with the cyclic stress range factor (f) in a determination process of the allowable stress range (S_A) in Eq. (3) associated with the calculation of the displacement stress range along with basic material allowable stresses. However, creep is implicitly considered in the determination process of the basic allowable material stress, which is determined as the minimum of the following three values at temperatures within the range where the creep and stress rupture strength govern the selection of stresses, and the maximum allowable stress is the lowest of the following [3]:

- 100% of the average stress to produce a creep rate of 0.01%/1000 h;
- 100 F_{avg}% of the average stress to cause a rupture at the end of 100,000 h; or
- 80% of the minimum stress to cause a rupture at the end of 100,000 h

where F_{avg} is the multiplier applied to the average stress for a rupture in 100,000 h.

At temperatures below the creep range, the maximum allowable stress is the lowest of the following:

- the specified minimum tensile strength at room temperature divided by 2.4;
- the specified minimum yield strength divided by 1.5;
- the yield strength at a temperature divided by 1.5 except for austenitic stainless steels, nickel alloys, copper alloys, and cobalt alloys; or
- 90% of the yield strength for austenitic stainless steels, nickel alloys, copper alloys, and cobalt alloys.

As previously described, the allowable stresses to be used in a design evaluation for significant and negligible creep cases are defined in a totally different manner. In the case of significant creep range, it is not a creep-lifetime-based value with a time fraction rule such as in the cases of ASME-HB [2] and RCC-MRx [9], but rather is a rule associated with the creep strain rate (0.01%/1000 h or equivalently 1%/100,000 h) and creep rupture stress at 100,000 h under load-controlled stresses.

Another thing to note is that, although the creep properties (creep rupture stress and creep strain rate) of 100,000 h are used for the design of high-temperature piping, B31.1 is actually used for piping to be operating over a plant design lifetime of 30–40 years or longer. The operators of power plants are usually operating piping systems longer than 100,000 h along with fitness for service or condition assessment monitoring through periodic metallurgical evaluations of the pipe. They monitor the creep deformation over time in terms of swelling along with hardness testing and surface replication to evaluate the microstructure. Measuring the creep swelling strain is an easy and economical means to assess the creep strain rate; once the creep strain reaches a certain value (e.g., 2%) in the field, it is considered the start of accelerated creep deformation and supplementary testing is conducted. Because B31.1 does not basically cover the operation time in a creep range longer than 100,000 h, such extensive in-service inspections are conducted as a complementary tool because it does not explicitly consider creep effects.

B31.1 is considered more suited for temperatures below the creep range, although it is commonly used for high-temperature piping as well. The maximum allowable stresses in B31.11 are up to 649 °C (1200 °F) for Type 316 family austenitic stainless steels (316, 316H, 316L, and 316 N) and Mod.9Cr-1Mo (ASME Grade 91) steel.

2.3 Design evaluations according to ASME B31.1

The piping system in the secondary loop of a large-scale sodium test facility, STELLA-2 [7], was used as an example problem in this study and the ANSYS 1-D finite element pipe element model of hot leg piping is shown in Fig. 1. The design temperature and pressure of the hot coolant at a steady state in the test facility are 550 °C and 0.5 MPa, respectively. The specifications of the hot leg piping in STELLA-2 are provided in Table 1.

The stress analysis results using the 1D pipe model shown in Fig. 1 under sustained and thermal loads are shown in Fig. 2. The locations of the maximum stress intensity under sustained loads are the built-in points as

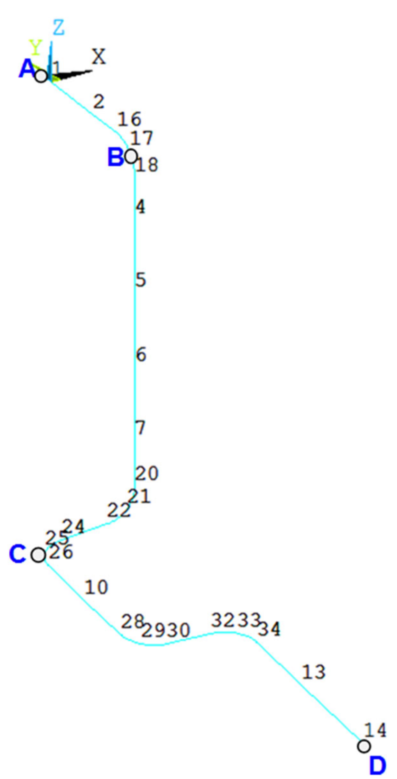

Fig. 1 Finite element model for a secondary piping system in a large-scale sodium test facility, STELLA-2

Table 1 Specification of 316L hot leg piping in a large-scale sodium test facility

Material	Size (in., SCH)	OD (mm)	Wall thickness (mm)
A-312, TP316L	4″, 20S	114.3	4.0

shown in Fig. 2a and the elbow locations of the base metal under thermal loads as shown in Fig. 2b. All evaluation results according to ASME B31.1 are shown in Table 2, and as shown, all the results are within the allowable limits.

Notably, the evaluation results from B31.1 are the same regardless of the hold time within the creep range, which means the design evaluation results should be the same regardless of the hold time at high temperature.

3 Design evaluation of high-temperature piping according to RB-3600

3.1 Treatment of creep in RB-3600 of RCC-MRx

The RB-3600 rule in the French nuclear grade high-temperature design rule, RCC-MRx, which is also a design-by-rule similar to B31.1, explicitly considers the effects of creep and creep–fatigue interaction. The actual design evaluation results differ depending on the hold time at high temperature.

In RB-3600, creep usage (U) under primary loads, creep rupture usage (W) under general loads, and creep–fatigue usage ($V + W$) under creep–fatigue loads are quantitatively determined from Eqs. (6), (7), and (8), respectively.

$$U = \sum_{j=1}^{N} \left(\frac{t_j}{T_j} \right), \tag{6}$$

$$W = \sum_{k=1}^{M} \left(\frac{t_k}{T_k} \right), \tag{7}$$

$$V + W = \sum_{i=1}^{p} \left(\frac{n_i}{N_i} \right) + \sum_{l=1}^{m} \left(\frac{t_l}{T_l} \right), \tag{8}$$

where t_j, t_k, and t_l are the hold time applied for load types j, k, and l, respectively. In addition, T_j, T_k, and T_l are the allowable time durations determined from the stress-to-rupture curves during the time intervals of j, k, and l, respectively, and M, p, and m are the number of different cycle types. n_i is the number of applied repetitions of cycle type i and N_i is number of design allowable cycles for cycle type i.

Evaluations of type P damage (monotonic loading) and type S damage (cyclic loading) should be separately conducted with (significant creep) and without (negligible creep) creep consideration. For evaluations of type

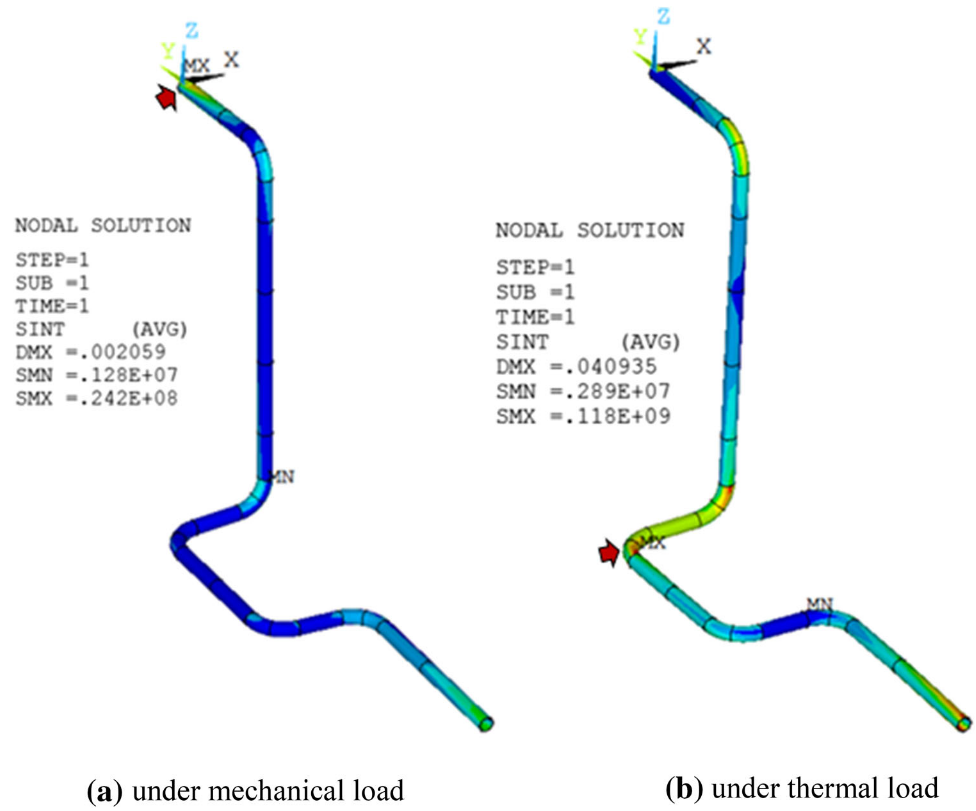

Fig. 2 Stress analysis results for 1D pipe element model

Table 2 Design evaluation results per B31.1 for hot leg piping

Node	Part	ASME B31.1					
		Mechanical loads			Thermal loads		
		Calculated	Limit	Ratio	Calculated	Limit	Ratio
1	Butt weld	34.4	60.0	0.57	26.9	184.4	0.15
14	Butt weld	19.7	60.0	0.33	193.7	199.2	0.97
16	Elbow	2.3	60.0	0.04	83.6	216.6	0.39
18	Elbow	7.7	60.0	0.13	92.2	211.2	0.44
20	Elbow	6.7	60.0	0.11	119.1	212.2	0.56
22	Elbow	4.4	60.0	0.07	133.9	214.5	0.62
24	Elbow	2.8	60.0	0.05	143.4	216.0	0.66
26	Elbow	4.0	60.0	0.07	136.3	214.8	0.63
28	Elbow	5.2	60.0	0.09	74.7	213.6	0.35
30	Elbow	5.1	60.0	0.09	46.0	213.7	0.22
32	Elbow	6.4	60.0	0.11	22.8	212.5	0.11
34	Elbow	7.2	60.0	0.12	60.8	211.6	0.29

P damage and type *S* damage, evaluations of negligible creep and significant creep should be conducted.

3.2 Design evaluations according to RCC-MRx RB-3600

The same piping evaluation results shown in Fig. 2 were used for the design evaluation according to RB-3600 of RCC-MRx. RB-3600 explicitly considers the effects of creep and creep–fatigue interaction in high-temperature piping design and can be more reliably used compared to those of B31.1, which implicitly considers creep in the form of load-controlled creep rupture stresses rather than creep rupture lifetimes based on time fraction rules. Because it treats time-dependent creep effects in the design-by-rule, the design evaluations require relatively more complicated calculations. Therefore, a computational program that can perform the design evaluations according to RB-3600 procedures in a more efficient and reliable manner was developed in a previous study [14] and used in the present evaluations. Because the design evaluation procedures as per RB-3600 are quite complicated with explicit consideration of the creep and creep–fatigue interactions in a number of relevant equations, the design evaluations using the program should be more reliable and efficient.

Design evaluations according to RB-3600 which explicitly considers creep were conducted for six different hold times of 150 h (6 d), 360 h (15 d), 720 h (30 d), 2160 h (90 d), 3600 h (150 d), and 7200 h (300 d) to assess the effects of hold times using the same model and loading conditions. As shown in Table 3 and Fig. 3, the design evaluation results according to RB-3600 showed that creep–fatigue damage limits were within the allowable limits up to 720 h (30 d). In Table 3 and Fig. 4, P_m is the general primary membrane stress intensity, P_L is the local primary membrane stress intensity, S_m is the design stress intensity, Φ is the coefficient dependent on the geometry of the cross section, P_1 is the effective primary stress intensity, P_2 is the effective primary stress intensity of the sum of primary stresses, $\varepsilon_{plastic}$ is the plastic strain, and ε_{creep} is the creep strain.

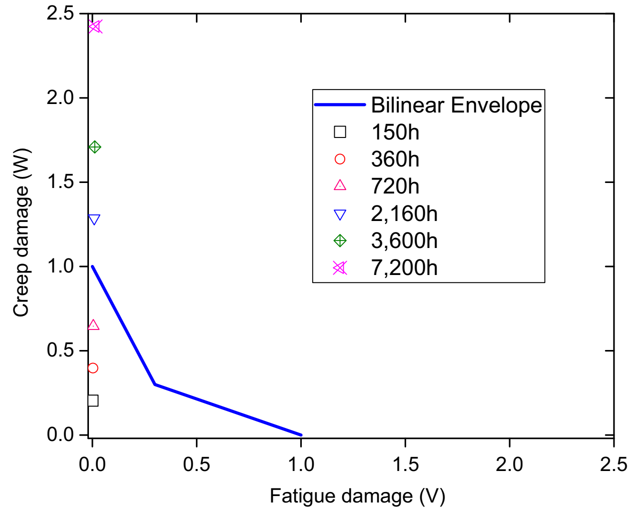

Fig. 3 Evaluation results of creep–fatigue damage as per RB-3600 depending on hold time

After 720 h, creep–fatigue limits were exceeded as shown in Table 3 and Fig. 3, which show the results depending on the hold times. Nomenclatures for the terms of Table 3 are provided in 'Nomenclature's section. The

Table 3 Evaluation results of a hot leg piping system as per RCC-MRx RB-3600 under various hold times in the creep regime

Design evaluation results according to RB-3600 of RCC-MRx									
Material	316L								
Maximum wall temperature	550								
Evaluation items			Limit value	Calculated					
Hold time (h)/day			•	150/6	360/15	720/30	2160/90	3600/150	7200/300
Type P damage	Negligible creep	$P_m < S_m$	77.0	6.94	6.94	6.94	6.94	6.94	6.94
		$P_m + P_b < 1.3\ S_m$	101.5	16.87	16.87	16.87	16.87	16.87	16.87
		$S_m + S_b < S^*$	47.84	9.95	9.95	9.95	9.95	9.95	9.95
	Significant creep	$U(\Omega P_m)$	1.0	6.00E−16	1.44E−15	2.88E−15	8.64E−15	1.44E−14	2.88E−14
		$U(P_m + P_b)$	1.0	2.65E−11	6.35E−11	1.27E−10	3.81E−10	6.35E−10	1.27E−9
		$W(1.35P_m)$	1.0	1.38E−8	3.31E−8	6.63E−8	1.99E−7	3.31E−7	6.63E−7
		$W[1.35(P_m + \Phi P_b)]$	1.0	2.13E−6	5.11E−6	1.02E−5	3.07E−5	5.11E−5	0.0001
Type S damage	Negligible creep	$P_1 < 1.3\ S_m$	101.5	30.764	30.764	30.764	30.764	30.764	30.764
		$P_2 < 1.3 \times 1.5\ S_m$	130.13	47.95	47.95	47.95	47.95	47.95	47.95
		$\text{Max}(P_m + P_b) + \text{Max}\ q(j, j') < 3\ S_m$	231	153.17	153.17	153.17	153.17	153.17	153.17
		Fatigue damage	1.0	0.0013	0.0027	0.0045	0.0086	0.0115	0.0156
	Significant creep	$\varepsilon_{plastic} + \varepsilon_{creep}\ (1.25\ P_1) < 1\%$	1.0	0.0109	0.0158	0.0211	0.0336	0.0416	0.0558
		$\varepsilon_{plastic} + \varepsilon_{creep}\ (1.25\ P_3) < 2\%$	2.0	0.0411	0.0591	0.0789	0.1249	0.1547	0.2069
		Fatigue damage	Bilinear envelope	0.0013	0.0027	0.0045	0.0086	0.0115	0.0156
		Creep damage		0.2037	0.397	0.6461	1.2863	1.7089	2.4235
Evaluation result			•	OK!!	OK!!	OK!!	Fail!!	Fail!!	Fail!!

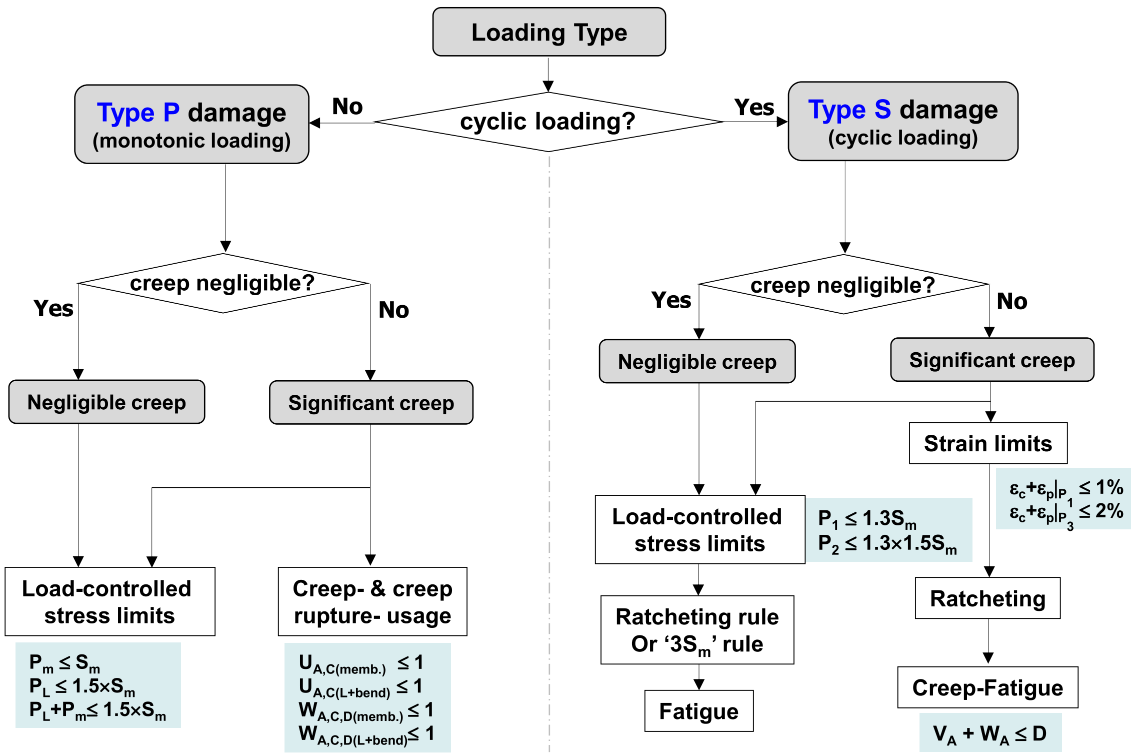

Fig. 4 Flow diagram of high-temperature design evaluations in RCC-MRx

stress levels of the piping system are not that high as shown in Fig. 2b under thermal loads. However, creep damage gradually increased as the operation time lengthened and finally the creep–fatigue damage exceeded the allowable envelope at the hold time of 2160 h as shown in Fig. 3 and Table 3. The creep damage was evaluated based on Robinson's time fraction rule of Eq. (7), and the total creep damage increased as the operational time lengthened under repeated creep–fatigue load cycles.

The present analysis results of hold times based on the RB-3600 rule showed that creep damage tended to exceed the limits of RB-3600 as operational times gradually increased as shown in Table 3. The results show an important finding that the B31.1 results, which were within the allowable limits (bilinear envelope) regardless of the hold time in the concept of RB-3600, exceeded the creep damage limits of RB-3600 as shown in Fig. 3.

4 Design evaluation of high-temperature piping according to RB-3200

4.1 Treatment of creep in RB-3200 of RCC-MRx

The RB-3200 rule in RCC-MRx explicitly considers the effects of creep and creep–fatigue interaction similar to RB-3600, but it is a design-by-analysis (DBA) rule based on finite element (FE) analysis of piping systems with three-dimensional (3D) solid elements rather than 1D pipe elements. The actual design evaluation results differ depending on the hold time at high temperature.

Similar to the case of RB-3600, creep usage (U) under primary loads, creep rupture usage (W) under general loads, and creep–fatigue usage ($V + W$) under creep–fatigue loads in RB-3200 were determined using Eqs. (6), (7), and (8), respectively.

The overall design evaluation procedures of RCC-MRx for the pressure boundary components are shown in Fig. 4. As shown in Fig. 4, evaluations of type P damage (monotonic loading) and type S damage (cyclic loading) should be separately conducted with (significant creep) and without (negligible creep) creep consideration. For evaluations of type P damage and type S damage, evaluations of negligible and significant creep should be separately conducted.

4.2 Design evaluations for high-temperature piping according to RCC-MRx RB-3200

For evaluation according to the rule of DBA, RB-3200, 3D solid elements were used; the FE model of the piping layout is shown in Fig. 5. The total number of 3D elements and nodes was 82,800 and 110,560, respectively.

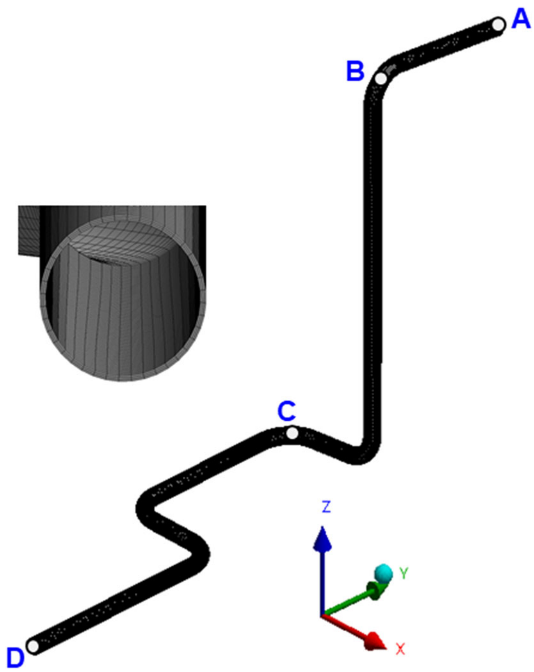

Fig. 5 Finite element modeling of the secondary piping system with 3D solid elements

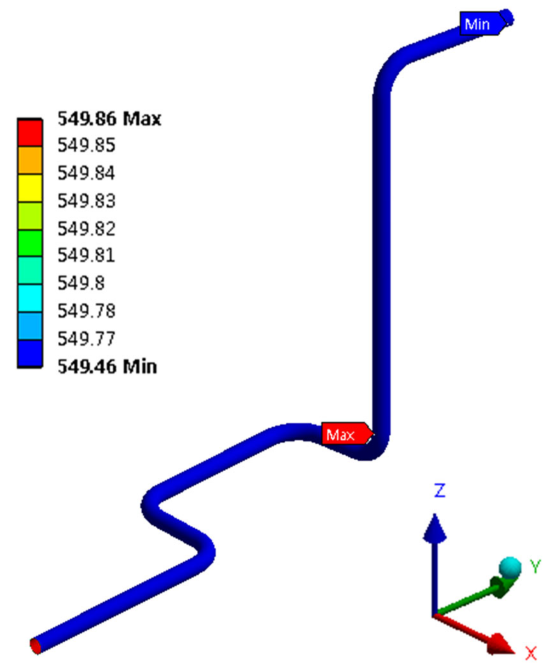

Fig. 6 Heat transfer analysis results of the secondary piping with 3D solid FE elements

First, heat transfer analysis was conducted, and the temperature profile was obtained as shown in Fig. 6 with a maximum wall temperature of 549.86 °C. From stress analysis, the profiles of the stress intensity under a mechanical load are shown in Fig. 7 in which the maximum stress intensity (SI) of 28.28 MPa was obtained at the top built-in point while under thermal loads. The maximum SI of 192.46 MPa was obtained at the curved pipe point of the base metal as shown in Fig. 8.

Design evaluations according to the DBA rule of RB-3200 were also conducted using HITEP_RCC-MRx [14]. The design evaluations according to RB-3200 also explicitly considered the creep effects, and case studies depending on hold times were conducted for six different hold times of 150, 360, 720, 2160, 3600, and 7200 h for the same model and same loading conditions. The stress levels of the piping system were not that high as shown in Fig. 8. However, the design evaluation results according to RB-3200 listed in Table 4 show that the creep–fatigue damage limit was within the allowable limits up to 2160 h (90 d) but thereafter these limits were exceeded under repeated creep–fatigue load cycles as shown in Table 4 and Fig. 9.

The analysis results of hold times based on the DBA rule of RB-3200 which explicitly considers creep effects show that creep damage tends to exceed the limits of RB-3200 as operational times gradually increase as shown in Fig. 9, similar to the case of RB-3600. The results show that the B31.1 results, which were within the allowable limits regardless of the hold time, exceeded the creep damage limits of RB-3200. However, comparing the degree of conservatism, the evaluation results of RB-3600 were more conservative than those of RB-3200, as shown in the creep damage values of Tables 3 and 4.

5 Sensitivity analysis of creep for ASME B31.1 AND RB-3600

The effects of creep were investigated through sensitivity analyses of the hold times over the range of 150 h (6 d) to 7200 h (300 d) from the evaluations, as per RB-3600. It was shown from the sensitivity analysis that the design limits of RB-3600 were not satisfied for hold times longer than 2160 h (90 d) in the case studies, as shown in Table 3, although the design limits of B31.1 were consistently satisfied regardless of the hold time, as shown in Table 2. Therefore, the hold times do have an effect on the high-temperature integrity of the plant as shown in Table 3; thus, the design evaluations as per B31.1 might be non-conservative in the case of a long-term operation at high temperature.

Because RB-3600 is a design rule with a safety margin, the design evaluation results exceeding the design limits do not exactly mean that an actual failure would occur. However, it signals that an actual failure could occur as the hold time increases during long-term operation at high temperature, which is the case in actual power plants.

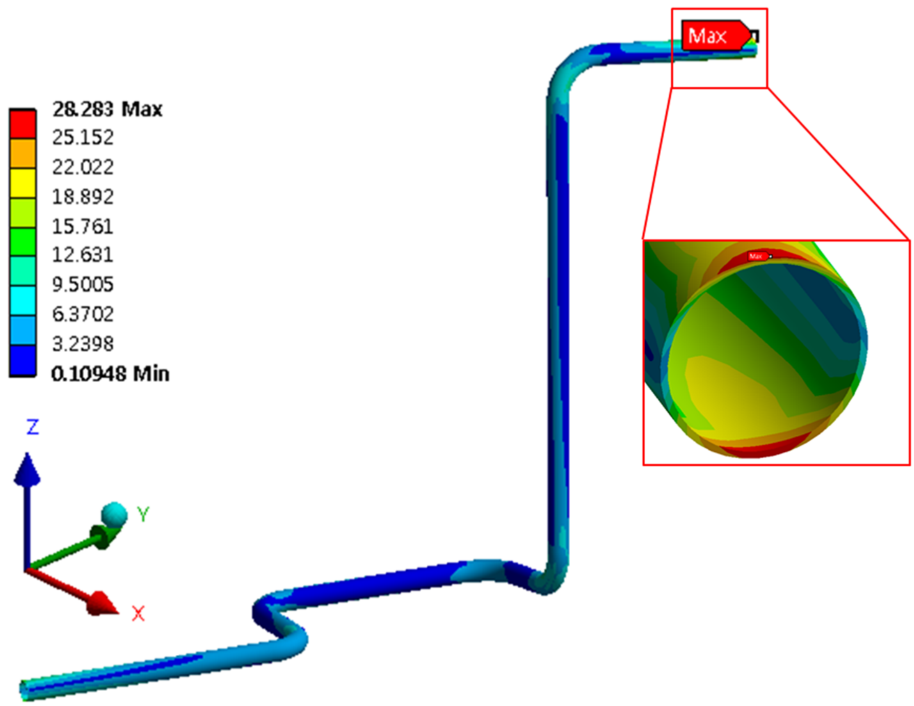

Fig. 7 Stress analysis results of the secondary piping under mechanical loads

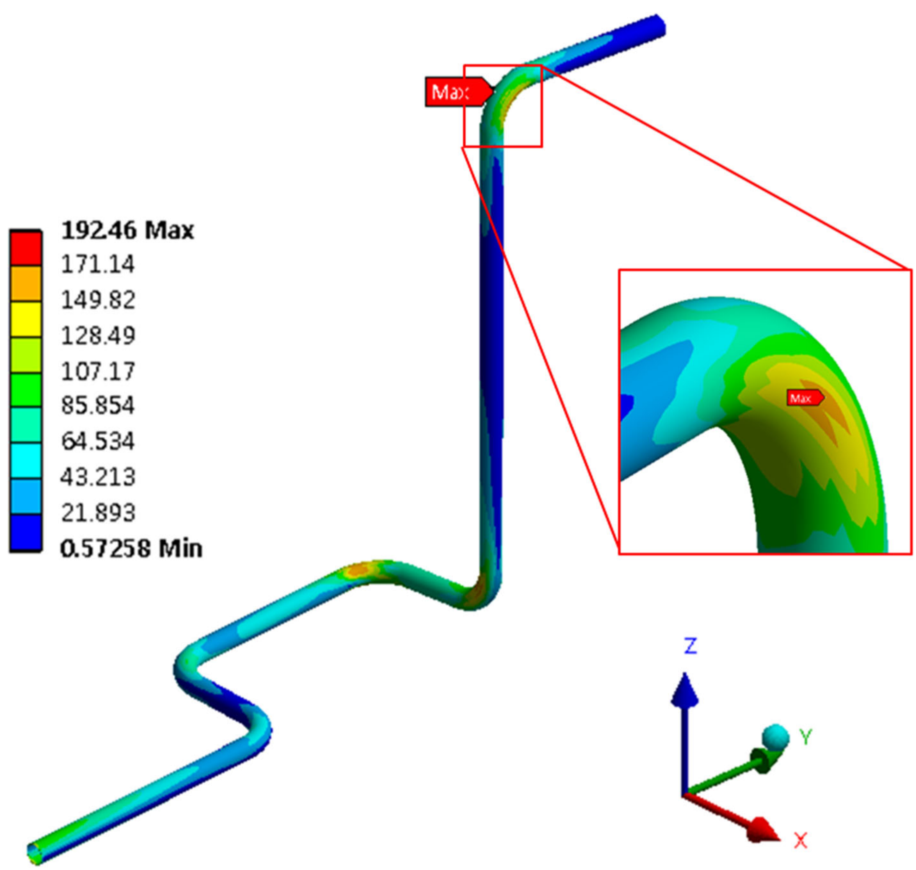

Fig. 8 Stress analysis results of the secondary piping under thermal loads

The evaluation results of the creep–fatigue damage depending on the six operational periods were compared as shown in Figs. 3 and 9. The evaluation results under a bilinear envelope mean that they are within the design limits. It is clear from the present sensitivity analysis that creep and creep–fatigue damage is not properly considered in B31.1.

Table 4 Evaluation results of a hot leg piping system as per RCC-MRx RB-3200 under various hold times in the creep regime

Design evaluation results according to RB-3200 of RCC-MRx									
Material	316L								
Maximum wall temperature	550								
Evaluation items			Limit value	Calculated					
Hold time (h)/day			•	150/6	360/15	720/30	2160/90	3600/150	7200/300
Type P damage	Negligible creep	$P_m < S_m$	77.0	13.06	13.06	13.06	13.06	13.06	13.06
		$P_L < 1.5\ S_m$	115.5	13.06	13.06	13.06	13.06	13.06	13.06
		$P_L + P_b < 1.5\ S_m$	115.5	13.06	13.06	13.06	13.06	13.06	13.06
	Significant creep	$U(\Omega P_m)$	1.0	3.18E−12	7.64E−12	1.53E−11	4.58E−11	7.64E−11	1.53E−10
		$U(P_m + P_b)$	1.0	5.171E−12	1.24E−11	2.48E−11	7.44E−11	1.24E−10	2.48E−10
		$W(1.35P_m)$	1.0	7.85E−7	1.89E−6	3.77E−6	1.13E−5	1.89E−5	3.77E−5
		$W[1.35(P_m + \Phi P_b)]$	1.0	9.87E−7	2.37E−6	4.74E−6	1.42E−5	2.37E−5	4.74E−5
Type S damage	Negligible creep	$P_1 < 1.3\ S_m$	100.1	42.96	42.96	42.96	42.96	42.96	42.96
		$P_2 < 1.3 \times 1.5\ S_m$	150.15	43.84	43.84	43.84	43.84	43.84	43.84
		$\text{Max}(P_m + P_b) + \text{Max}\ q(j, j') < 3\ S_m$	231	154.87	154.87	154.87	154.87	154.87	154.87
		Fatigue damage	1.0	5.72E−6	1.67E−5	3.37E−5	0.0001	0.0002	0.0006
	Significant creep	$\varepsilon_{plastic} + \varepsilon_{creep}\ (1.25\ P_1) < 1\%$	1.0	0.0335	0.0482	0.0645	0.1021	0.1265	0.1693
		$\varepsilon_{plastic} + \varepsilon_{creep}\ (1.25\ P_3) < 2\%$	2.0	0.0356	0.0512	0.0684	0.1084	0.1343	0.1797
		Fatigue damage	Bilinear envelope	5.72E−6	1.67E−5	3.37E−5	0.0001	0.0002	0.0006
		Creep damage		0.1241	0.2493	0.417	0.8711	1.1842	1.7316
Evaluation results			•	OK!!	OK!!	OK!!	OK!!	Fail!!	Fail!!

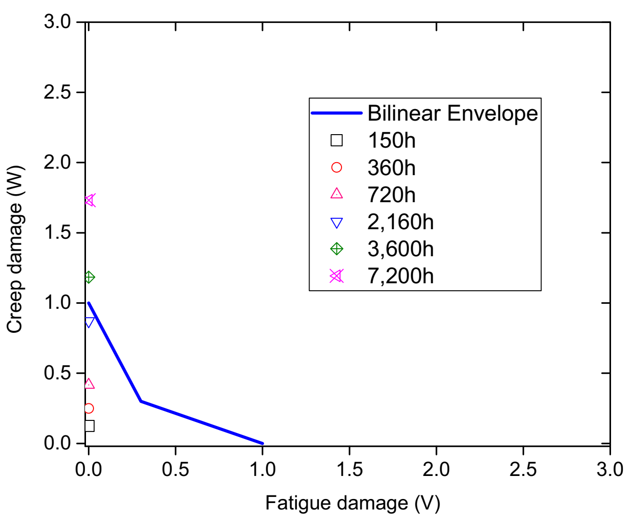

Fig. 9 Evaluation results of creep–fatigue damage as per RB-3200 depending on hold time

In the case of a piping system subjected to long-term operation at high temperature in the creep regime, the RCC-MRx RB-3600 and RB-3200, which explicitly consider the creep effect, would be more appropriate than ASME B31.1.

Because the design rules of ASME B31.3 [16] for process piping are very similar to those of B31.1 for power piping in terms of implicit creep consideration, the same logic in the present study would be applied to ASME B31.3.

The operating temperatures of power or process plants tend to increase to as high as 600 °C for higher efficiency and therefore the essential importance of creep effects should become more prominent. Based on the present study, it is highly recommended to conduct design evaluations in parallel with the design codes of RB-3200, RB-3600, or HBB-3200 that explicitly consider the creep effect to ensure the safety of piping systems designed according to ASME B31.1 subjected to long-term high-temperature operation in a creep regime.

6 Conclusion

A sensitivity analysis of the hold time at high temperature in the creep regime was conducted to investigate the conservatism of ASME B31.1 for piping design subjected to long-term operation and the risks of non-conservatisms were quantified. ASME B31.1 implicitly considers creep effects through a determination procedure of maximum allowable stresses. The design evaluation results of the secondary piping of the STELLA-2 test loop according to B31.1 show that the design limits are satisfied regardless of the hold time. However, those of RCC-MRx RB-3600, and RB-3200, which explicitly consider creep, change depending on the hold times. A sensitivity analysis of the hold time showed that in the case of RB-3600, the design limits were exceeded when the hold time exceeded 2160 h, while in the case of RB-3200, 3600 h.

Two important aspects should be noted. First, the design evaluations according to B31.1 might be non-conservative in the case of a long-term operation at high temperature because its evaluation results were within the design limits regardless of the hold time. Second, the DBA results as per RB-3200 are less conservative than those of the simplified design-by-rule results as per RB-3600. Based on the present study, it is highly recommended to conduct design evaluations as per RB-3200, RB-3600, or HBB-3200 in parallel with ASME B31.1 to ensure long-term safe and reliable operation at high temperature in a creep regime.

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