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THE ULTIMATE STRENGTH OF CYLINDRICAL LIQUID STORAGE TANKS UNDER EARTHQUAKES
- Seismic Capacity Test of Tanks Used in PWR Plants -
(Part2 : STATIC POST-BUCKLING STRENGTH TESTS)

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ABSTRACT
Since 2002, Japan Nuclear Energy Safety Organization (JNES) has been carrying out seismic capacity tests for several types of equipment which significantly contribute to core damage frequency. The primary purpose of this study is to acquire the seismic capacity data of thin walled cylindrical liquid storage tanks in nuclear power plants and to establish an evaluation procedure of the ultimate strength.

As for the refueling water storage tank and the condensate storage tank which are used in PWR plants, elephant-foot bulge (EFB) is the typical buckling behavior of those tanks and the primary failure mode to be focused on. In the previous study, by conducting the dynamic and static buckling tests with aluminum alloy, it was confirmed that static buckling test represents dynamic buckling and post-buckling behavior in terms of energy absorption capacity. In this study, static buckling tests with actual material were performed in order to evaluate the ultimate strength of real tanks. Although the buckling mode did not differ among materials, tests with actual materials (steel, stainless steel) resulted higher seismic capacity compared to the aluminum alloy, and inner water leakage occurred from the cracks initiated at the secondary buckling on the EFB section.

INTRODUCTION
In September 2006, Nuclear Safety Commission of Japan revised the seismic design guideline for nuclear power plant. The guideline newly requires that residual risk for huge earthquakes should be considered. Seismic probabilistic safety assessment (PSA) is an available method to evaluate the residual risk of nuclear power plant and there has been a growing desire to improve the reliability of the seismic PSA.

Since 2002, JNES has been carrying out seismic capacity tests for several types of equipment which significantly contribute to core damage frequency. The refueling water storage tank and the condensate storage tank are among such kind of important equipment. The primary purpose of this study is to acquire the seismic capacity data of those tanks.

There has been a lot of study on the seismic behavior of cylindrical liquid storage tanks; however, few have focused on seismic capacity related to dynamic buckling behavior. Shibata et al. [1],[2] made comprehensive researches on the damage to liquid storage tanks due to actual earthquakes all over the world, and made a long-term monitoring study with a thin-walled tank model exposed to actual earthquakes. In addition, after the devastating Hanshin-Awaji earthquake (1995), a large number of damage investigations were made on liquid storage tanks [3],[4].

As for laboratory studies, Akiyama et al. made a series of buckling tests with tank models [5]-[7]. With the large-scale shaking table in Tadotsu, The High Pressure Gas Safety Institute of Japan [8] and Japan Power Engineering and Inspection Corporation [9] conducted earthquake resistance tests on liquefied natural gas storage tanks.

Buckling modes of cylindrical liquid storage tanks include bending buckling (elephant foot bulge (EFB) and diamond buckling), shear buckling, and buckling behavior of the upper part of tanks due to nonlinear ovaling vibration of sidewall, which induces plastic deformation on the sidewall and eventually makes vibration behavior of whole tank nonlinear. In the previous study that focused on the buckling behaviors mentioned above, dynamic buckling tests with 1/3-1/5 reduced test models of PWR refueling water storage tank and condensate storage tank were conducted[10]～[11]. EFB developed in both cases, and it was observed that leakage of inner liquid occurred at the EFB cross-section, that is, functional limit of the tanks was dominated by EFB. In addition, the nonlinear ovaling vibration was observed around the upper region; however, it was confirmed that the vibration and EFB in the lower section did not interfere each other. Besides, it was concluded that the nonlinear ovaling vibration did not lead to cracking of the sidewall because amplitude of the vibration saturated as the input earthquake level increases. In the following studies, a new design concept, in which the response reduction effect due to post-buckling energy absorption was taken into account in buckling criteria, was proposed [12].

The previous study was mainly conducted to grasp the buckling characteristics of the water storage tanks under seismic condition and to propose the design criteria based on the buckling. So there is merely one case of large-scale buckling test data using a refueling water storage tank model. From the view point of the seismic PSA, it is desired to obtain the ultimate strength data, or capacity data of actual tanks which can be utilized for the seismic PSA.

nomenclature

E^*	: Ratio of Young's modulus
L	: Tank height
P_f	: Static pressure
Q	: Weight
R	: Radius
S_e	: Earthquake input acceleration level
T	: Time
F	: Subscript for liquid or frequency
P	: Subscript for structure or pressure
S	: Subscript for structure
t	: Thickness
ρ	: Density

PURPOSE

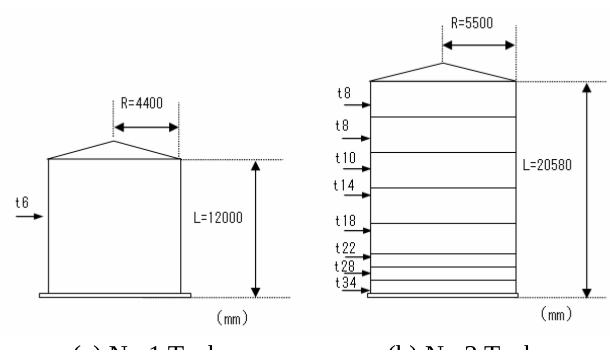
In general, median and deviation of seismic capacity are necessary to carry out the seismic PSA. But in the case where seismic capacity of a certain component is many times higher than design level, deviation is not so important for the seismic PSA. In other words, if the seismic capacity is so high that the residual risk of nuclear power plants is small enough to satisfy the safety goal, an effect of the deviation would be negligible.

As for water storage tanks which are included in safety system, the seismic capacity is expected to be high but there is a lack of data about the seismic capacity and failure mode, especially there is few data of actual tank material. The purpose of this study is to acquire the strength seismic capacity data of liquid storage tanks and to establish a strength evaluation method for actual equipment, targeting EFB that is considered to be critical for the functional limit of tanks.

In this 2nd report of 2 consecutive studies, “Static post-buckling strength test” is presented and discussed. The primary purpose of this study is to evaluate, the ultimate strength of the tanks with actual materials. Taking accounting for the findings from the 1st study, static post-buckling strength evaluation test was conducted with small tank models which were fabricated so as to simulate the lower part of the tanks and were made of actual tank materials (steel or stainless steel). The test was conducted statically because it was verified in the 1st report that the static buckling test can simulate the dynamic buckling test by accommodating the static hoop stress at the lower part of tank to the dynamic test (hoop stress in the dynamic test is caused by dynamic pressure and static head).

ACTUAL TANKS AND TEST MODELS

Figure 1 illustrates dimensions of tanks in this study. No.1 Tank has uniform thickness and No.2 has varying thickness. Table 1 shows the dimensions of typical actual tanks and test models. Evaluation method verification test (dynamic and static) targeted No.1 tank and static post buckling strength test targeted No.1 and No.2 tanks. It is noted that the No.2 tank was modeled above the buckling section only and the thickness of the sidewall was simplified as uniform thickness. When designing test specimen, FEM analyses (ABAQUS) were performed in order to predict the buckling mode and load. The result of the analyses is briefly explained in Appendix A. According to the pre-analyses, only EFB occurred in No.1 tank. On the other hand, in No.2 tank, shear buckling occurred at the side wall perpendicular to the loading direction as well as EFB.



(a) No.1 Tank (b) No.2 Tank

Fig.1 Outline of Typical Actual Tanks

Table 1 Dimensions of Tanks

	No.1 Tank		No.2 Tank	
	Actual Tank	Test model	Actual Tank	Test model
Scale ratio	1/1	1/12	1/1	1/20
Material	Steel	Aluminum alloy, Steel, Stainless Steel	Stainless steel	Aluminum alloy
Diameter (mm)	8800	734	11000	550
Tank height (mm)	12000	614	20580	287
Thickness (mm)	6	0.5	8～34	0.5

STATIC POST-BUCKLING STRENGTH TESTS

Test Methods

Test Specimen. In order to investigate the post-buckling strength of actual tanks, static buckling tests with tank models of actual material were conducted. It was verified in the 1st report (Evaluation method verification test) that static buckling test can simulate the buckling behavior and the seismic level at ultimate state of dynamic buckling test by adjusting hoop stress condition at the lower part of tank. As discussed in the previous report, initial pressure statically included dynamic pressure component. Figure 2 illustrates the test model of No.1 and No.2 tank.

(a) No.1 Tank model (b) No.2 Tank model

Fig.2 Overview of Tank Models

Loading Profile. In the static post-buckling strength tests, tank-top displacement was simulated and loaded with an actuator as shown in Figure 3 as well as the static buckling test of evaluation method verification test which was described 1st report.

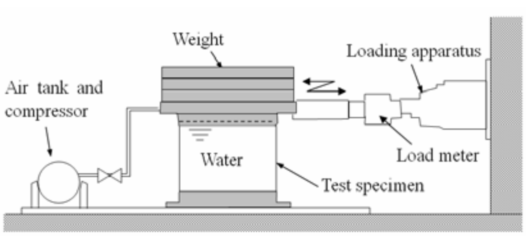
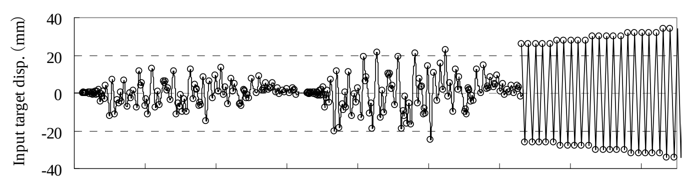


Fig.3 Static Buckling Test Apparatus

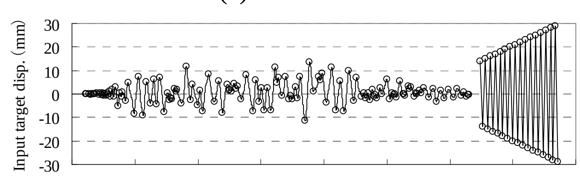
Test Conditions. In the static post-buckling strength tests, input target displacement was calculated by nonlinear response analysis of the actual tank, and the target input level was adjusted to the level at which the actual tank reached its ultimate state by a single earthquake. The nonlinear response analysis uses single degree of freedom system which is assumed hysteresis diagram by the same approach with previous studies [12].

Figure 4 shows the time history of target input displacements of the No.1 Tank and No.2 Tank. Both displacements consisted of serial and incremental input displacements in cases where the tanks could not reach their ultimate state by single input displacement. Figure 5 presents an example of the target displacement calculation flow for No.1 tank. In the case of the No.1 Tank, the target level of the first input displacement is about 5.25 times of the original input seismic wave which is shown in Figure 4. If the tank did not reach the ultimate state by this input load, the buckling test was continued by using a second input load of target displacement which was about 6.0 times of the original input seismic wave. Moreover, if the tank did not reach ultimate state by the second input load, buckling test was continued by using incremental sinusoidal wave until the tank reached ultimate state. The test of No.2 Tank was performed in the same manner. In the case of No.2 Tank, first target level of the input displacement was about 9.9 times of the original input seismic wave.

In addition, in the test of No.1 Tank, aluminum alloy, steel and stainless steel test models were tested in order to evaluate the difference among materials on buckling behavior and seismic capacity. For No.2 Tank, only stainless steel test model, which is same material of actual tank, was tested.



(a) No.1 Tank



(b) No.2 Tank

Fig.4 Target Input Disp.

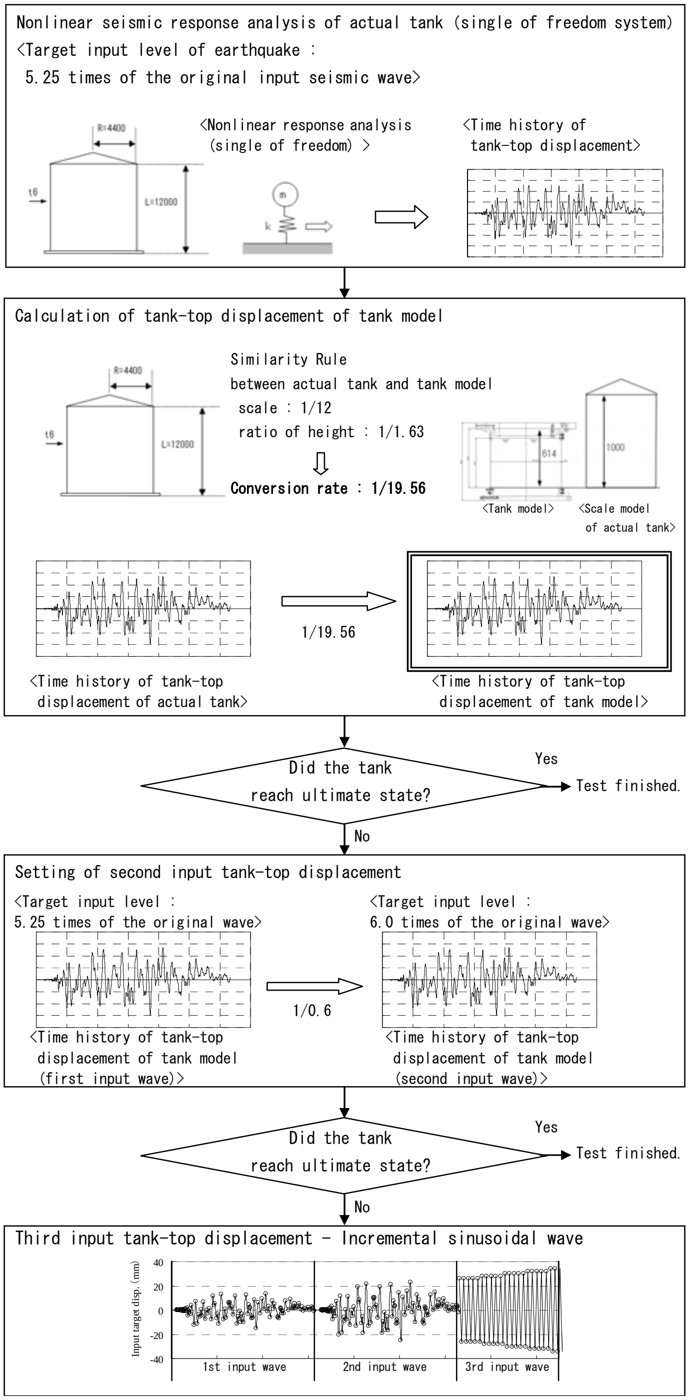


Fig.5 Calculation Flow of Target Displacement of No.1 Tank

Measurement Items and Methods. Along with the static buckling test of the evaluation method verification test (1st report), displacement was measured with non-contact laser displacement sensors that were placed around the top of the tank. Local strains, especially strains around the buckling region (tank bottom), were measured with strain gauges. In addition the inner pressure was measured with pressure meters.

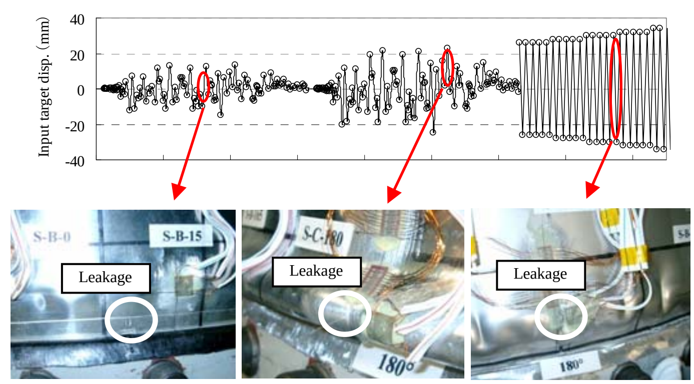
Test Results

No.1 Tank Model. As predicted by FEM analysis (Appendix A), EFB occurred in all test models as shown in Figure 6, thus it is known that buckling behavior of the tank does not depend on the tank materials (aluminum alloy, steel and stainless steel).

In the test of the aluminum alloy model, internal water leaked from a crack at the lower fringe of the EFB, just like in the dynamic buckling test of the evaluation method verification test, during the test of the first target input level. In the test of the steel model, internal water leaked from a crack on the secondary buckling which occurred upon the EFB during the test of the second target input level. Equally in the test of the stainless steel model, internal water leaked from a crack on the secondary buckling which occurred upon the EFB during the test of the third target input level. Figure 7 shows the ultimate state level and photos of water leakage condition of each of the test models. It is concluded that the buckling behavior is represented by EFB regardless of tank materials, but the ultimate state level is clearly different. The test results show that the ultimate state of aluminum alloy appears at lower load level. As a consequence, the aluminum alloy test gives more conservative results than the actual tank materials (steel and stainless steel). Consequently, considering that the actual material of No.1 Tank is steel, it is likely that the ultimate state of the actual tank of No.1 may exceed nearly 5 times of the original seismic level.

(Aluminum alloy) (Steel) (Stainless steel)

Fig.6 Elephant Foot Bulge



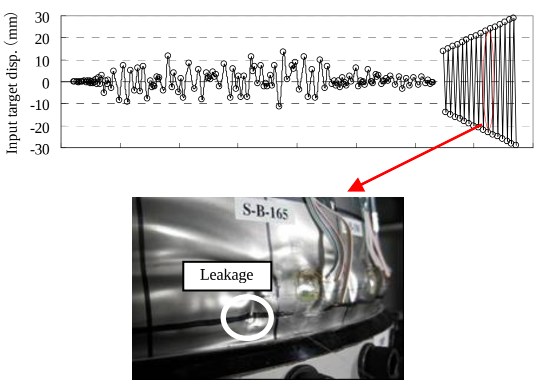
(Aluminum alloy) (Steel) (Stainless steel)

Fig.7 Comparison of Ultimate State Level of Test Models

No.2 Tank Model EFB in the loading direction and shear buckling at the direction perpendicular to the loading direction occurred at the almost same time. This simultaneous buckling behavior was predicted by FEM analysis (Appendix A). Figure 8 shows photos of the buckling behavior of the tank after the first target input load. In the test, internal water leaked from a crack on the secondary buckling which occurred upon the EFB during the test of the second target input load. Figure 9 shows the ultimate state level and a photo of the water leakage condition. Moreover, considering that the actual material of No.2 Tank is stainless steel, it is possible that the ultimate state of the actual tank of No.2 may exceed nearly 9 times of the original seismic level and leakage mode was a crack on the secondary buckling which occurred upon EFB, which was same as No.1 tank (actual material).

(Loading direction) (Perpendicular direction)

Fig.8 Photo of Elephant Foot Bulge and shear buckling



(Excitation direction)

Fig.9 Ultimate State Level of Test Model

CONCLUSIONS

In this study, static post-buckling strength test were performed using small tank models that were fabricated for simulating the lower part of the tanks, and seismic capacity data against EFB and post-buckling damage was obtained. The following findings and discussions are to be noted as conclusions.

(1) Buckling behavior of tank does not depend on tank materials (aluminum alloy, steel and stainless steel test). Rather, the buckling behavior is mainly affected by tank shape, size and inner pressure condition.

(2) From the test results, the ultimate state for accrual material tanks is water leakage from cracks on the secondary buckling which occurs upon the EFB.

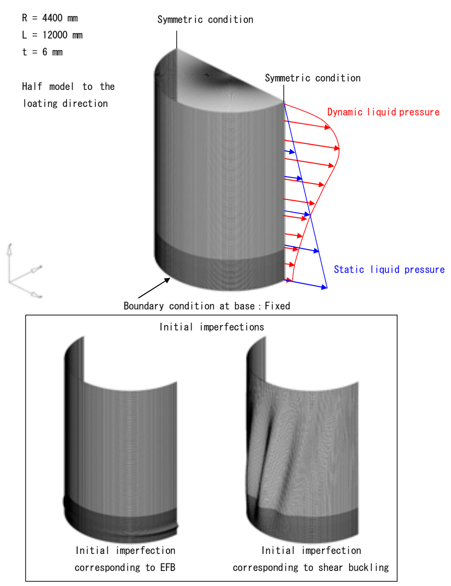
(3) From the comparison of the test results of different materials, it is observed that the ultimate state level is clearly different; the ultimate state level of aluminum alloy tank is smaller than that of the actual material tank , i.e., the aluminum alloy tank test is conservative compared with actual material (steel and stainless steel) tanks.

(4) Comparison of the input wave levels at which the EFB occurred and inner water leaked suggests that a large margin can be expected from the initial buckling to the ultimate state of actual tanks.

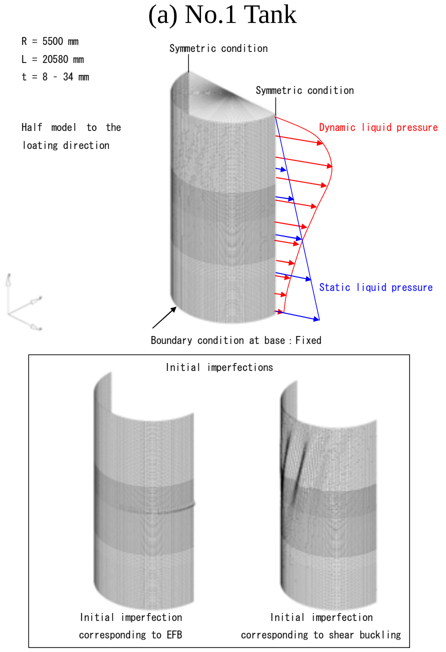
(5) As for the secondary buckling, which dominated the ultimate strength of the test tanks with actual materials, it is desirable to establish the evaluation method that can clarify the secondary buckling initiation condition (e.g. EFB deformation, loading condition, and input seismic level).

Appendix A: Pre-analysis for Tank Specimen Profile Design

In order to decide the shapes of test specimens and to verify buckling modes of them before tests, static elastic-plastic buckling analyses for actual tank models were conducted using ABAQUS. Dynamic fluid pressure by earthquake response of tank and static fluid pressure were considered as load condition. Dynamic fluid distribution is calculated using the theory presented by Fisher [13]. And initial imperfections corresponding to EFB and shear buckling mode are considered in each model. Because the load condition and the buckling mode are symmetric to the loading direction, FEM model can reduce to half-model (ref. Figure A1).



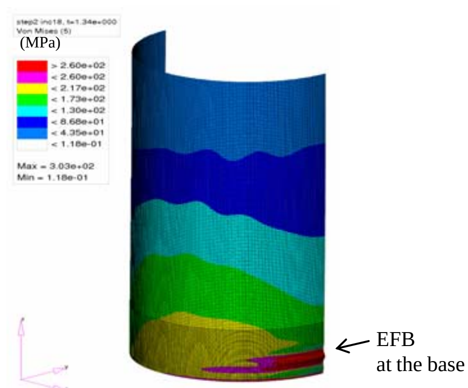
(a) No.1 Tank



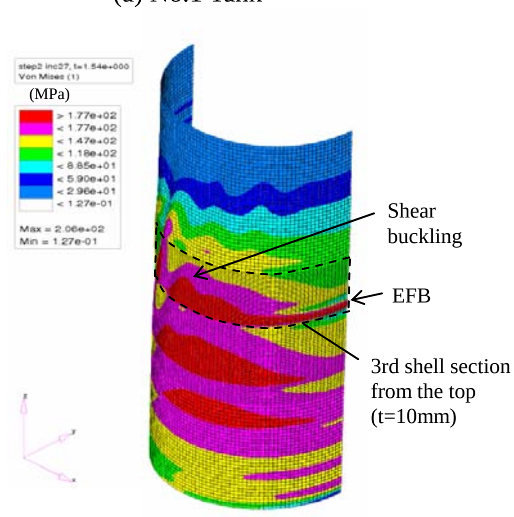
(b) No.2 Tank

Fig.A1 FEM Model and Load Condition

Buckling modes and Mises stress contours are presented in Figure A2. Only EFB occurred at the base of No.1 Tank. As for No.2 Tank, on the other hand, both EFB and shear buckling occurred simultaneously at the base line of 3rd shell section from the top (t=10mm). Taking account for this result, No.2 tank test model represents only above the buckling section, considering that the effect of lower section on the buckling behavior is negligible. It is noted that these buckling modes correspond to buckling tests (ref. Figure 8).



(a) No.1 Tank



(b) No.2 Tank

Fig.A2 Buckling Modes and Mises Stress Contours of Tank Models (Half model)

Appendix B: Mechanism of Secondary Buckling Initiation

In this study, the secondary buckling is regarded to follow the EFB deformation growth. The initiation mechanism is assumed as follows.

1) EFB initiates and grows as the loading level increases.

2) Once the EFB occurs, horizontal load creates compressive hoop stress along the EFB section in the opposite side of loading direction.

3) After the growth of EFB deformation beyond certain level, the compressive hoop stress happens to lead to the initiation of the secondary buckling, just as the bending buckling of the small piping.

Considering the mechanism mentioned above, it is assumed that the dominating factor of the initiation criteria for the secondary buckling is the deformation (out of the plane) of the EFB and horizontal loading level.

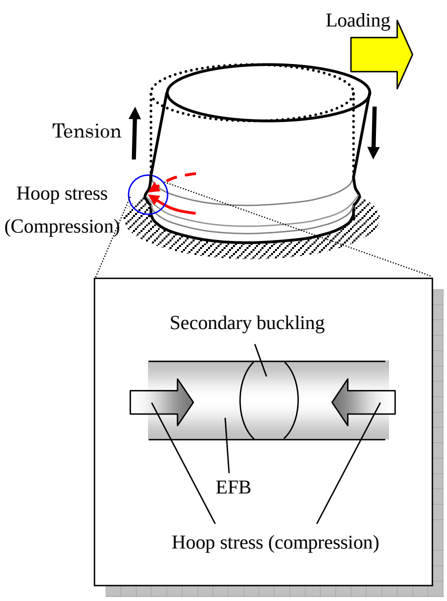


Fig.B1 Secondary Buckling Initiation Mechanism

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