Postbuckling Behavior of Windows Subjected to Synchrotron Radiation X-rays

Zhibi Wang, Tuncer M. Kuzay, and Sushil K. Sharma

Experimental Facilities Division
Advanced Photon Source
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439

Introduction

Synchrotron x-ray windows are vacuum separators and are usually made of thin beryllium metal. A thin wafer structure like a beryllium window will buckle if subjected to excessive thermal load from synchrotron radiation x-rays. If the bending stress or strain in the window after the buckling exceeds the limit values, the window will fracture causing leakage into the front end vacuum system. A very thin window will experience elastic buckling at the initial stage of the thermal buckling. With no additional loading, the original orientation of the window is restored after removal of the thermal load. Therefore, elastic buckling might be considered the normal working condition for some windows under very high heat loads due to the fact that thermal buckling may not result in a failure due to fracture. A full understanding of the behavior of windows after buckling would enable one to precisely predict the failure of the window as well as possibly incorporate elastic buckling into the window design. This paper will first review some test data as well as postbuckling behavior of similar structures under thermal or mechanical load, and then results of postbuckling analyses of beryllium windows subjected to x-ray thermal loads will be presented. The possibility of incorporating elastic buckling into window designs will be discussed.
Postbuckling of a panel under thermal and mechanical load

Tests by Maezawa and others [1,2] were performed on two 0.3-mm Be window assemblies with an aperture of 120 mm X 10 mm. The heat load was generated by Photon Factory BL-16A wiggler/undulator. The Be windows were at 16.85 m from the source. One window was made of hot-pressed Be ribbon and the other one of cross-rolled Be ribbon. The absorbed power was in the range of 27.5 W to 600 W. The tests showed that one window buckled due to thermal stress from the absorbed power, and the other buckled then broke and evaporated as shown in Figures 1. Wang and Kuzay [3] verified that the two windows were indeed buckled; one remained in plastically buckled even after the thermal load was removed; and the second window buckled and broke due to large bending tensile stress and low plasticity of the cross-rolled Be ribbon. Other window tests by Q. Shen et al. [4] featured a 0.25-mm Be window with an aperture of 50 mm X 6 mm. The test load was a 45 mm X 5 mm electron beam, starting from 100 W and ramped up in 20 W increments. The window cracked at 660 W. Analysis [3] showed that the window went into yield first and then plastically buckled at 660 W of heat load.

Beryllium manufacturer's technical data [5] on flat panels of beryllium (Figure 2) show that they exhibit postbuckling behavior similar to that of other metals. From Figure 2, it can be seen that the complete failure stress (initial buckling stress plus additional postbuckling stress) is still smaller than the yielding stress. This complete failure stress decreases as the thickness of the panel decreases, although the gap between the initial buckling and complete failure, that is, the postbuckling strength does increase as the thickness of the panel decreases. In other words, even after one considers increasing strength due to postbuckling, the load factor of a thin panel is not as large as that of a thick panel if the load density is a constant.

N. Kaniya et al. [6] analyzed finite deflection and postbuckling behaviors of heated rectangular elastic plates and considered temperature-dependent mechanical and thermal properties for the plates. Their numerical results [6] on two kinds of boundary conditions (rotation-free referred as BCa and rotation-constrained referred to as BCb) are shown in Figure 3. The curves in Figure 3 indicated that, before buckling, there was no deflection (without initial imperfection) or
very small deflection (with initial imperfection). At the buckling load level, the deflections change very fast as the thermal load changes very little and so does the thermal stress. The curves tend to shift up as the thermal load further increases, which we refer to as postbuckling strength. But this postbuckling strength is very limited compared with the total strength, especially for rotation-constrained case (BCb). The bending stress could cause the plate failure before the postbuckling strength becomes significant.

The postbuckling behavior due to thermal load here [6] is very similar to that of due to mechanical load [7]. Note that one of the differences of buckling behavior due to thermal load and mechanical load is that the Young's modulus plays different roles. The buckling load factor is proportional to the Young's modulus for a mechanically loaded panel, whereas the thermal buckling load factor is independent of the Young's modulus [3, 8]. Another difference of the postbuckling behavior of panels due to a thermal load and a mechanical load is that the membrane stress (axial stress) due to thermal load can be released after initial buckling but that due to the mechanical load cannot. This will be further proven by the analyses of this paper in the next section. However, because the bending stress will be dominant after initial buckling and this bending stress state has similar characteristics for both thermal and mechanical loaded panel, the postbuckling behavior of the panels under both thermal and mechanical loading remains the same.

Because there is still additional load carrying capacity after initial buckling, it is possible that the postbuckling of the thin panel structure, e.g., synchrotron radiation window, be utilized as part of total load carrying capacity. The main purpose of this paper is to investigate this possibility and make comparison of load carrying capacities between thin panels using the postbuckling capabilities and those without.

**Postbuckling analysis of a window under synchrotron radiation thermal load**

To study the postbuckling behavior of Be window, analyses is performed on a 10 mm X 70 mm aperture Be window with different thicknesses. The window is assumed to be fixed at its boundaries. The window frame is cooled by 30 °C water. The heat load for the window is
calculated assuming a 300-μm graphite filter is in front of the window. The ID used for power absorption is the APS Wiggler AHI.

The purpose of the analyses is to study the behavior of Be window after initial buckling. From this postbuckling analysis, we try to find out whether the load factor of a thin window at failure is larger than the load factor of a thick window that fails without buckling. For the thin window, it is assumed that the window will not fail at initial buckling until the bending stress after the buckling becomes so large that the window material will fail. For thick window, the failure mode is plastic deformation caused low-cycle-fatigue. As pointed out by [5], beryllium has an unusually high resistance to fatigue cracking and designers can use yield stress as the primary design criterion. Hence, another assumption is made here that when comparing the behavior of a thick window with a thin window, plastic deformation implies the failure of the window material.

For a 250-μm Be window, plastic deformation occurs before buckling. The total absorbed power on the Be window is 117.3 W. When the load factor is unity, full load is applied to the window. At this time, the maximum von Mises stress is at the level of yielding. When the load increases by a factor of 1.55, the window reaches the point of initial buckling, that is, the buckling load factor is 1.55. For a 100-μm Be window, the total absorbed power is 48.3 W, from which it can be seen that the total absorbed per unit thickness is a constant as pointed out by Wang and Kuzay et al. [9]:

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\frac{117.3 \text{ W}}{250 \mu \text{m}} = \frac{48.3 \text{ W}}{100 \mu \text{m}} = 0.48 \text{ W/μm}.
\]

The above relationship shows that the solution will not depend on the thickness if no buckling occurs. In both cases above, the maximum temperature is about 133 °C and minimum temperature is about 33 °C.

The 100-μm Be window has a buckling load factor of 0.6, that is, the window will buckle before the full beamline power is applied. Figure 4 shows the lateral deformation at the location of maximum value of the window versus analysis iteration number. This curve is analogous to Figure 2 in that it shows a postbuckling behavior of square plate under thermal loading. At the buckling load level, deformation increases much more while the load only increase very little.
Figure 5 depicts the stress in the window in the short direction (which is the main compression stress direction) in top, middle, and bottom layers at the location where the maximum lateral deflection occurs. Before buckling, the three stresses almost have same value. This means that the window is mainly in axial compression. Start from the buckling point, stresses at the top and bottom become dramatically different; top layer become in tension and bottom layer increases greatly in compression. The middle layer stress that represents an axial compression of the window becomes smaller because the lateral deformation or bending releases this axial compression. However, the thermal membrane stress (axial stress) released due to bending is very small compared with the bending stress at the top and bottom layers. The postbuckling buckling behavior of a window under a thermal loading can be characterized by a typical bending stress, which is caused by buckling rather than axial thermal strain, plus a uniform compression stress state (membrane stress) that has been partially released in magnitude after initial buckling. The bending part has the properties that tensile stress is equal to compression stress in magnitude. Because the bending stress after initial buckling is overwhelmingly larger than the membrane stress that has been partially released due to lateral deformation, the bending of the window after initial buckling will do more harm than help in reducing the magnitude of maximum stress.

The most important thing to notice is that shortly after the buckling, the bending stresses of top layer and bottom layer become so large that both tensile and compression stresses exceed the material yielding point. This means that the increased load factor from the buckling point to the last failure point is not big enough so that the total load factor to failure can be comparable with the load factor to failure of a thick plate. This has been clearly shown in Figure 3 for mechanical load where the complete failure after considering the postbuckling strength of the plate is always below the yielding point. The similar conclusion has been drawn here for Be window with thermal load under the condition that the thermal load density is a constant.

Figure 6 shows the deformation contour of the 100-μm window after buckling where there are three bumps (waves after buckling) in the center point out the paper and two bumps on the
sides into the paper. The bumps here bear the similarity to those seen in Figure 1 from the window tests.

Discussion and Conclusions

Analyses performed on two Be windows, one 250-μm thick and another 100-μm, show that the additional postbuckling strength still exists after the initial window buckling and this part can be used by a thin window design in the working stage. However the load factor to complete failure is not as big as the load factor to failure of a uniformly compressed window (this is the case for a thick window where buckling stress is larger than the yielding stress of the window material). That is the load factor of a thin window to collapse is not as large as that of a thick window without buckling. Hence, unless there is a special need for a thin window, such as the low energy photon transmission etc., buckling of the windows in normal working stage should not be recommended.

Due to complexity, shakedown is not considered here for both thick and thin window analyses, but similar conclusion can be expected, because by considering shakedown, load factors for thick and thin windows will be raised by a same factor.

Results here are based on finite element analyses. Experiments are being recommended to verify the analytical results.

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References


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Figure 1. The failure of two windows tested by Maczawa et al. [1,2]
Figure 2. Buckling behavior of beryllium panels [5]
Figure 3. Maximum deflection of square plate under thermal load [6]
Figure 4. Maximum deflection versus iteration number from the analysis.
Figure 5. Thermal stresses at top, middle, and bottom layers of the Be window
Figure 6. Deflection of window caused by synchrotron radiation beam