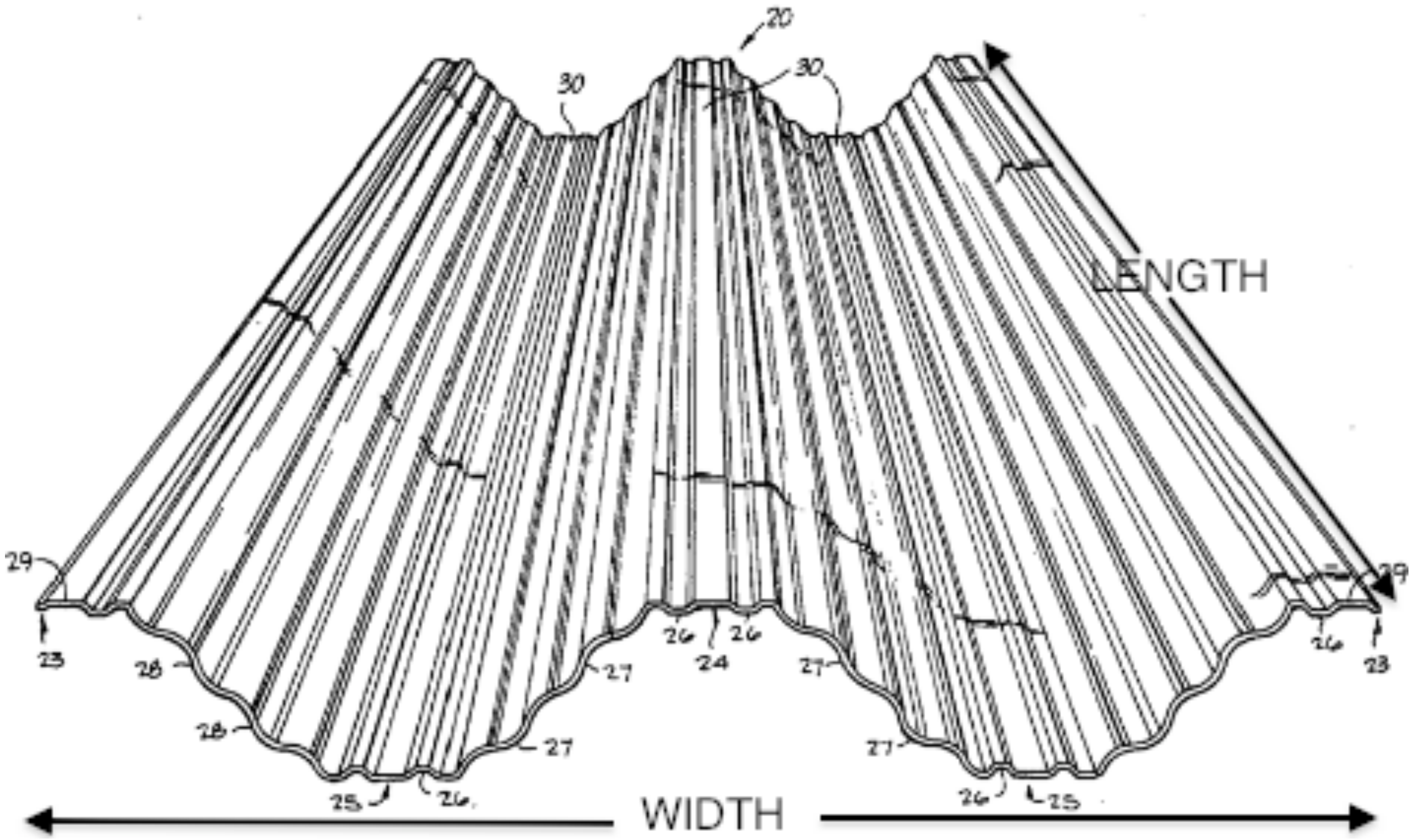


Fig. 1 **A prismatic corrugated panel with major and minor corrugations** of the type described in the invention by Lacasse [1]. This figure, minus the added overall dimensions, WIDTH and LENGTH, is from [1].

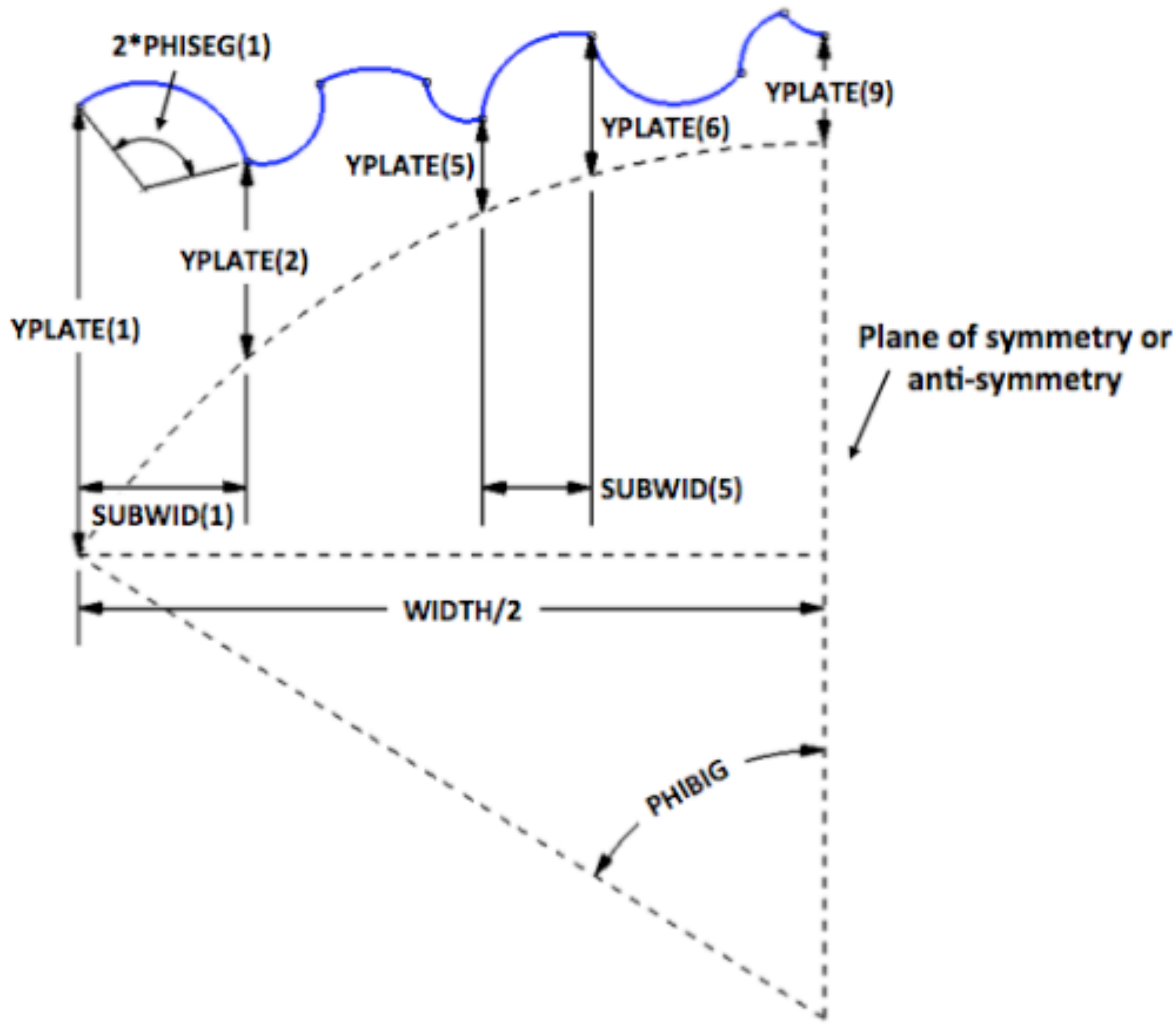


Fig. 2 **Sample optimized panel cross section profile** (blue) of half the width, WIDTH/2, of a complex corrugated panel with 8 major cylindrical segments over WIDTH/2 and with an alternating "convex surface up"/ "convex surface down" configuration. In this example there are no sub-segments. **The panel cross section was optimized by GENOPT/span9/BIGBOSOR4 by means of the GENOPT processor called "SUPERDUPEROPT"**. As shown in the next figure, the major segments are numbered starting from the left-most edge. PHIBIG is the overall arching angle in degrees. THICK(i) (the wall thickness of the ith major segment), SUBWID(i), and PHISEG(i), i = 1, 2, 3,…, NSEG, are decision variable candidates. ("Candidate" means "eligible to be a decision variable": a variable with designated Role No. 1 in Table 1.) The number of major segments, NSEG = 8, in this example. YPLATE(j), j = 1, 2, 3, …NSEG+1 are also decision variable candidates, and the overall arching angle, PHIBIG, is a decision variable candidate as well. In this example all of the decision variable candidates are decision variables except for YPLATE(1) and THICK(k), k = 2, 3, …, 8. The variables, THICK(k), 2 = 2, 3, …, 8, are all linked to THICK(1) with a linking constant = 1.0. Therefore, the entire optimized panel cross section is of uniform thickness, THICK(1).

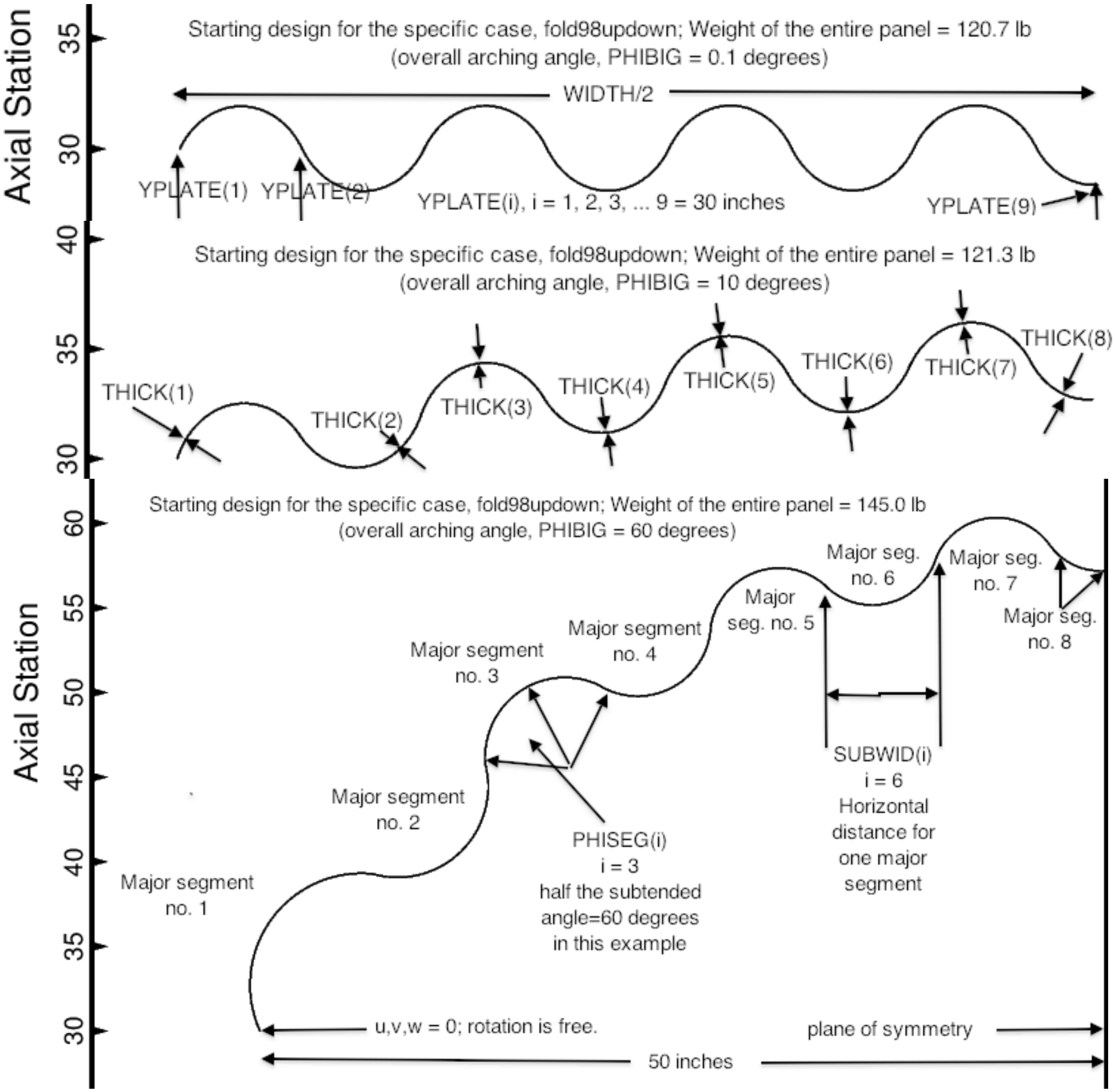


Fig. 3 **Sample starting designs of corrugated panels**, each with 8 major segments and with an alternating "convex surface up"/ "convex surface down" configuration. There are no sub-segments in this particular example, which is called **"fold98updown"**. Top: No overall arching (PHIBIG=0.1 degree); Middle: small overall arching (PHIBIG=10 degrees); Bottom: large overall arching (PHIBIG=60 degrees). The number of major segments over half the width, WIDTH/2, of the panel is NSEG=8. These plots are from the BIGBOSOR4 postprocessor called BOSORPLOT. The unfortunate label on the vertical axis, "Axial Station", is automatically produced by BOSORPLOT. It is appropriate for shells of revolution but not for prismatic shells. The left-hand boundary condition, "u,v,w = 0; rotation is free", is referred to as **"OLD"** in Section 4.

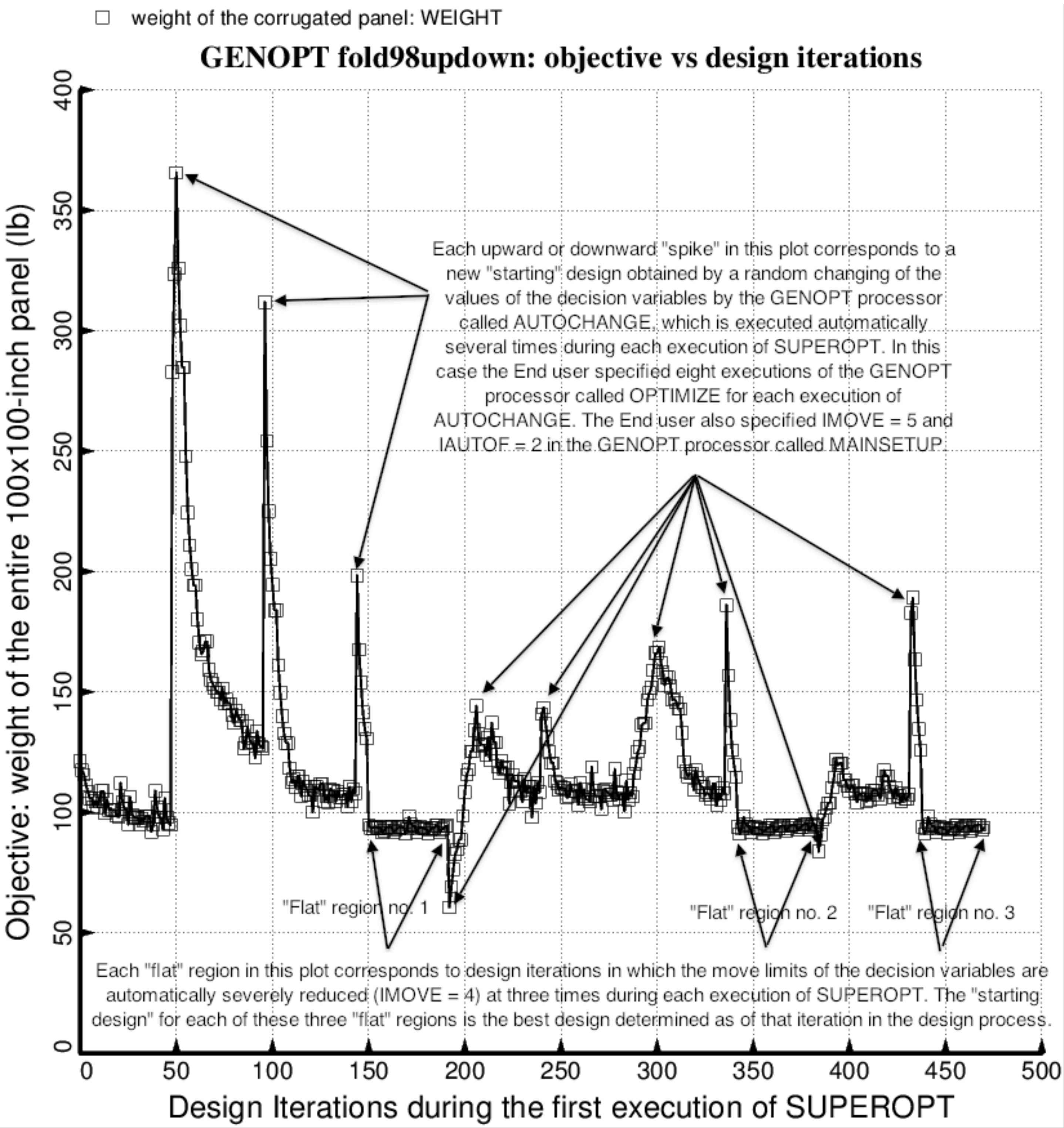


Fig 4 **Objective versus design iteration** during the optimization of the complex corrugated panel the starting design of which is displayed in the middle frame of the previous figure. The starting design corresponds to Iteration No. 0.

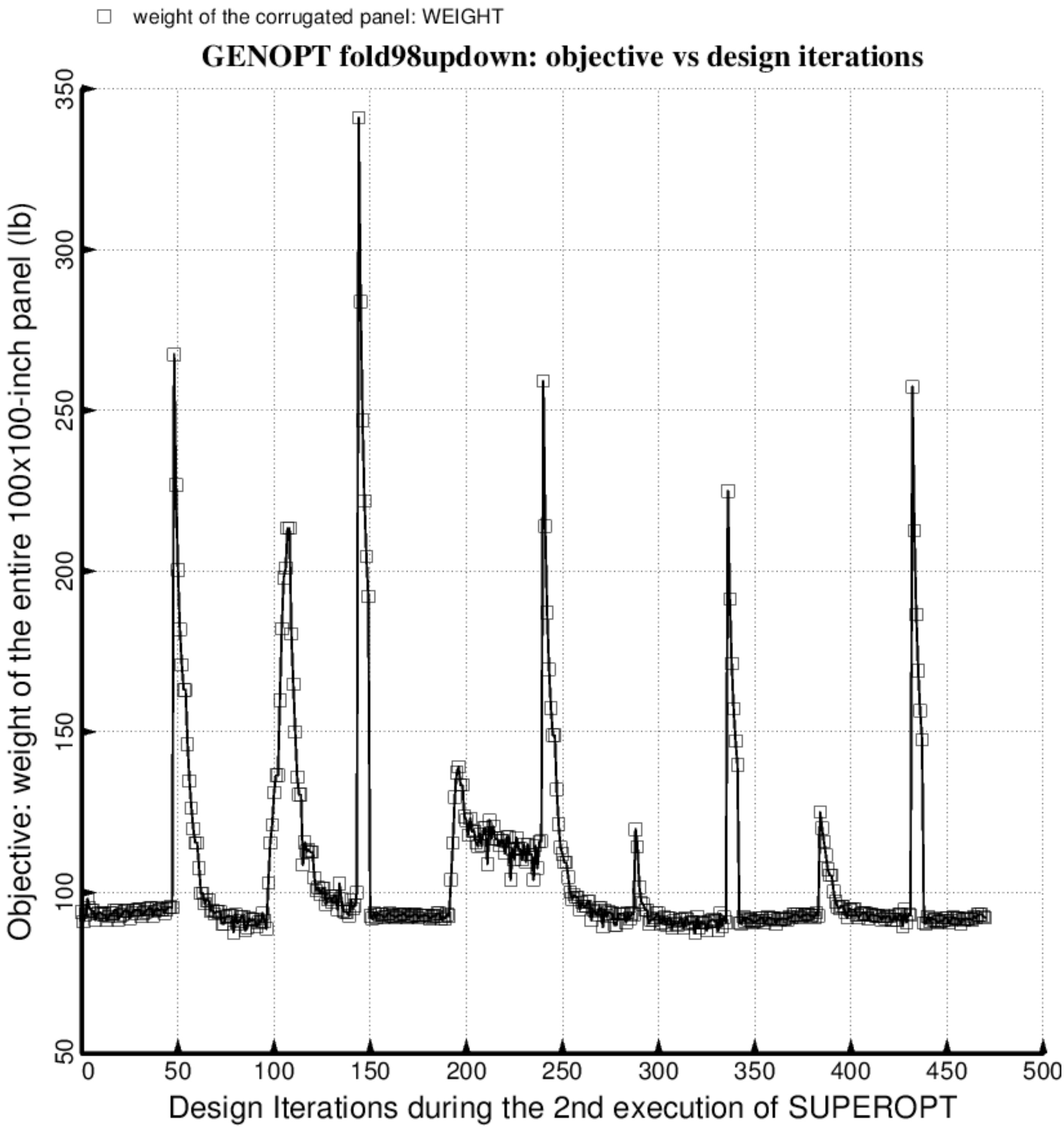


Fig 5 **Objective versus design iteration** during the continuing optimization of the complex corrugated panel in the execution of the GENOPT processor called “SUPERDUPEROPT”. The new “starting” design is the best design determined from the previous execution of SUPEROPT during the long SUPERDUPEROPT process. The new “starting design” corresponds to Iteration No. 0.

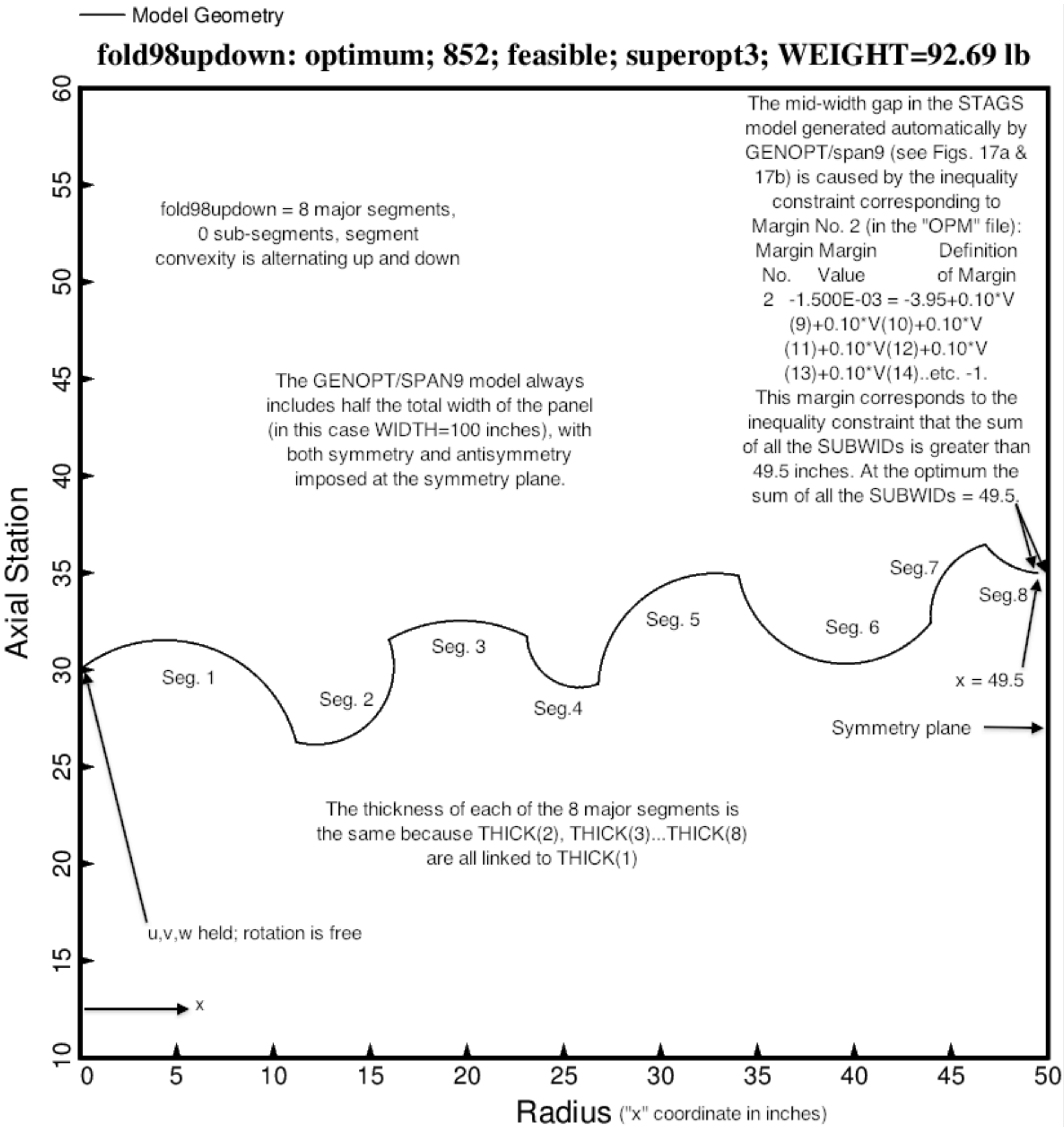


Fig. 6 **Optimized design of the panel cross section** for the specific case called “fold98updown”. This optimized panel cross section is the same as that shown in Fig. 2. The optimized weight of the entire panel of width, WIDTH = 100 inches is 92.69 lb. The STAGS model referred to above is shown in Fig. 20, not Fig. 17. The left-hand boundary condition, “u,v,w = held; rotation is free”, is referred to as **“OLD”** in Section 4.

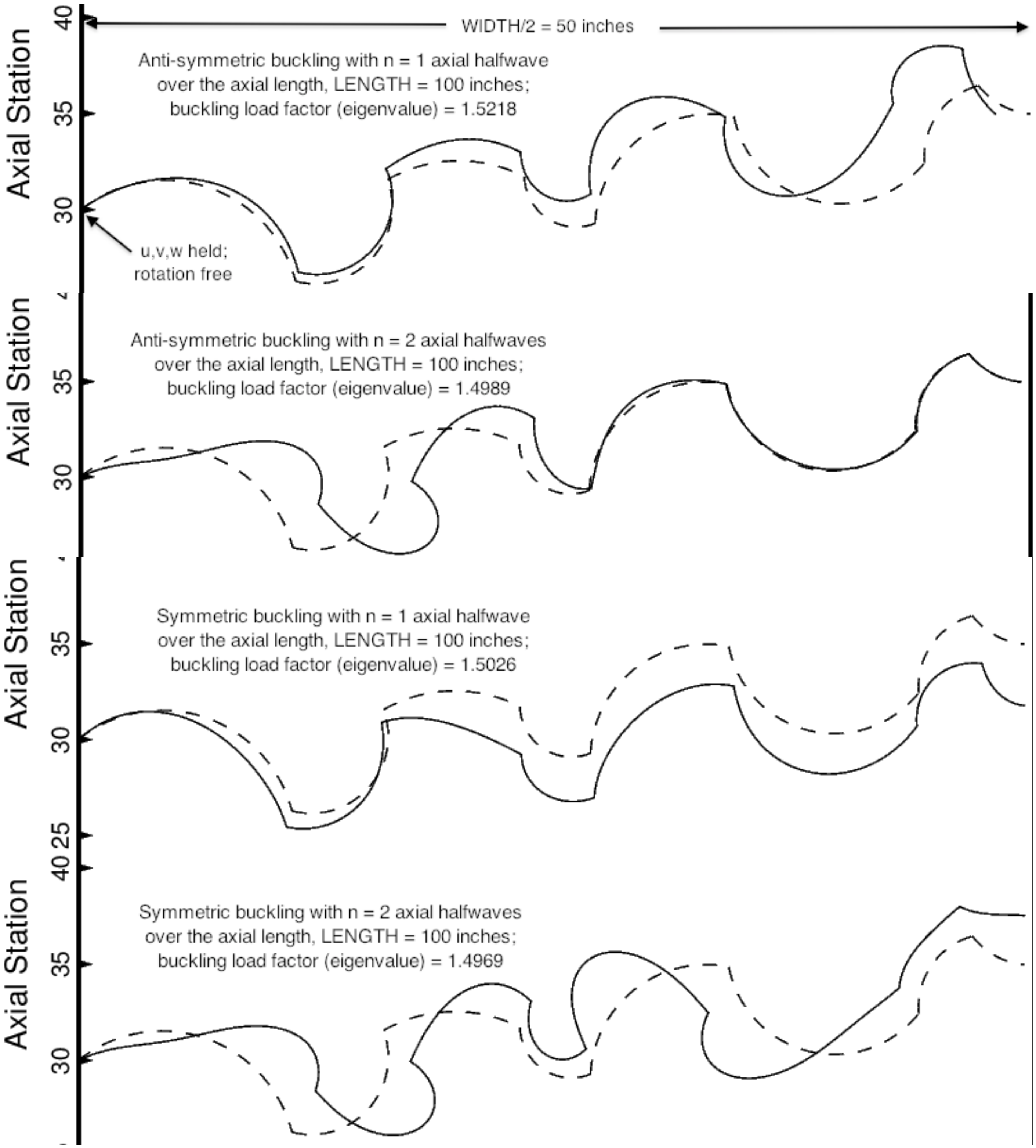


Fig. 7 **General buckling** of "fold98updown" anti-symmetric and symmetric at the mid-width symmetry plane. The left-hand boundary condition, "u,v,w = held; rotation is free", is referred to as **"OLD"** in Section 4.

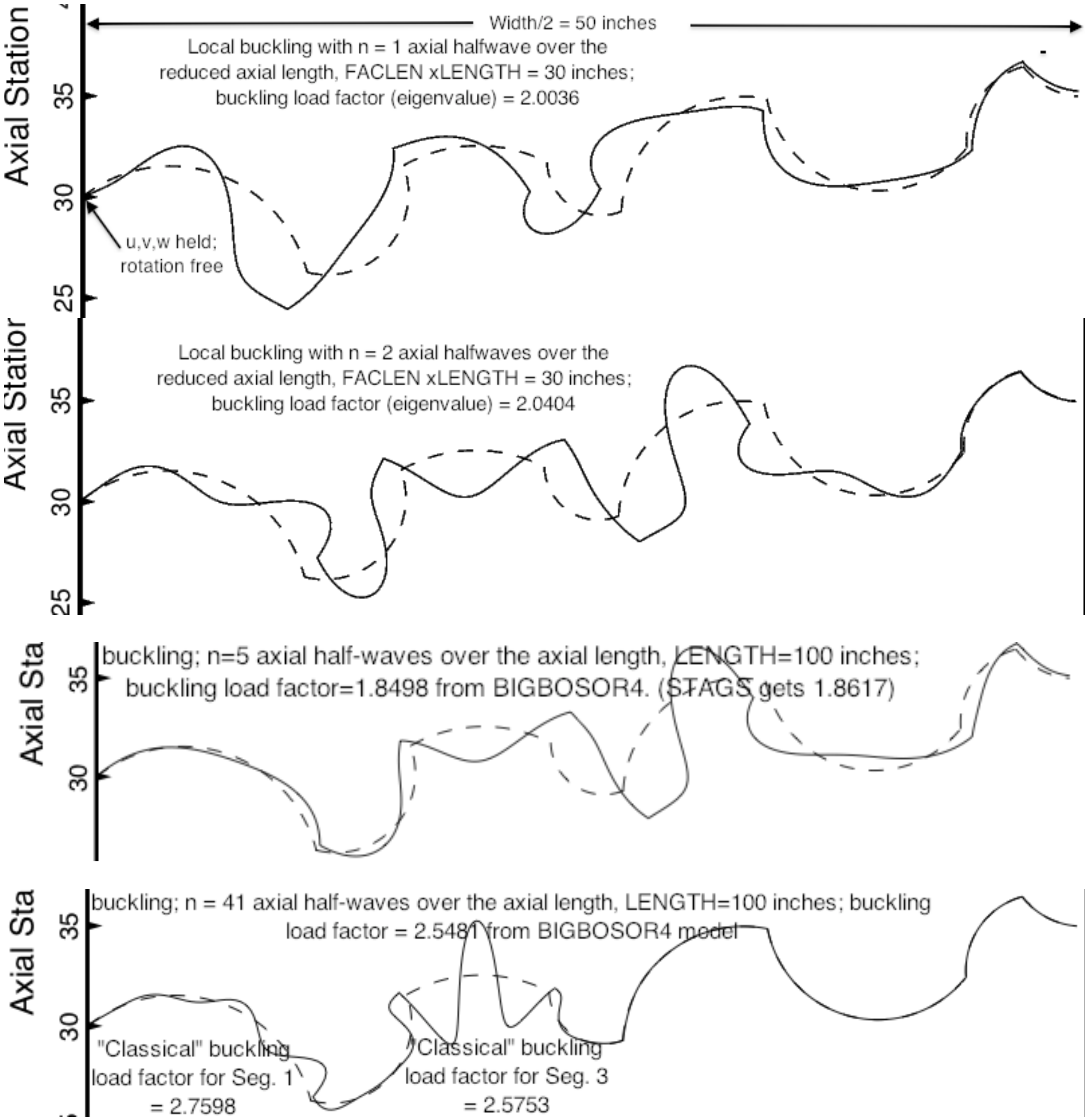


Fig. 8 **Local buckling** of the optimized "fold98updown" panel with n = 1, n = 2, n = 5 and n = 41 axial half waves over the reduced axial length, FACLEN x LENGTH = 0.3 x LENGTH = 30 inches. The WEIGHT of the entire optimized panel of WIDTH=100 inches is 92.69 lb, as is indicated in Fig.6, and the boundary condition along the left-hand longitudinal edge is "u,v,w held; rotation free", referred to as **"OLD"** in Section 4.

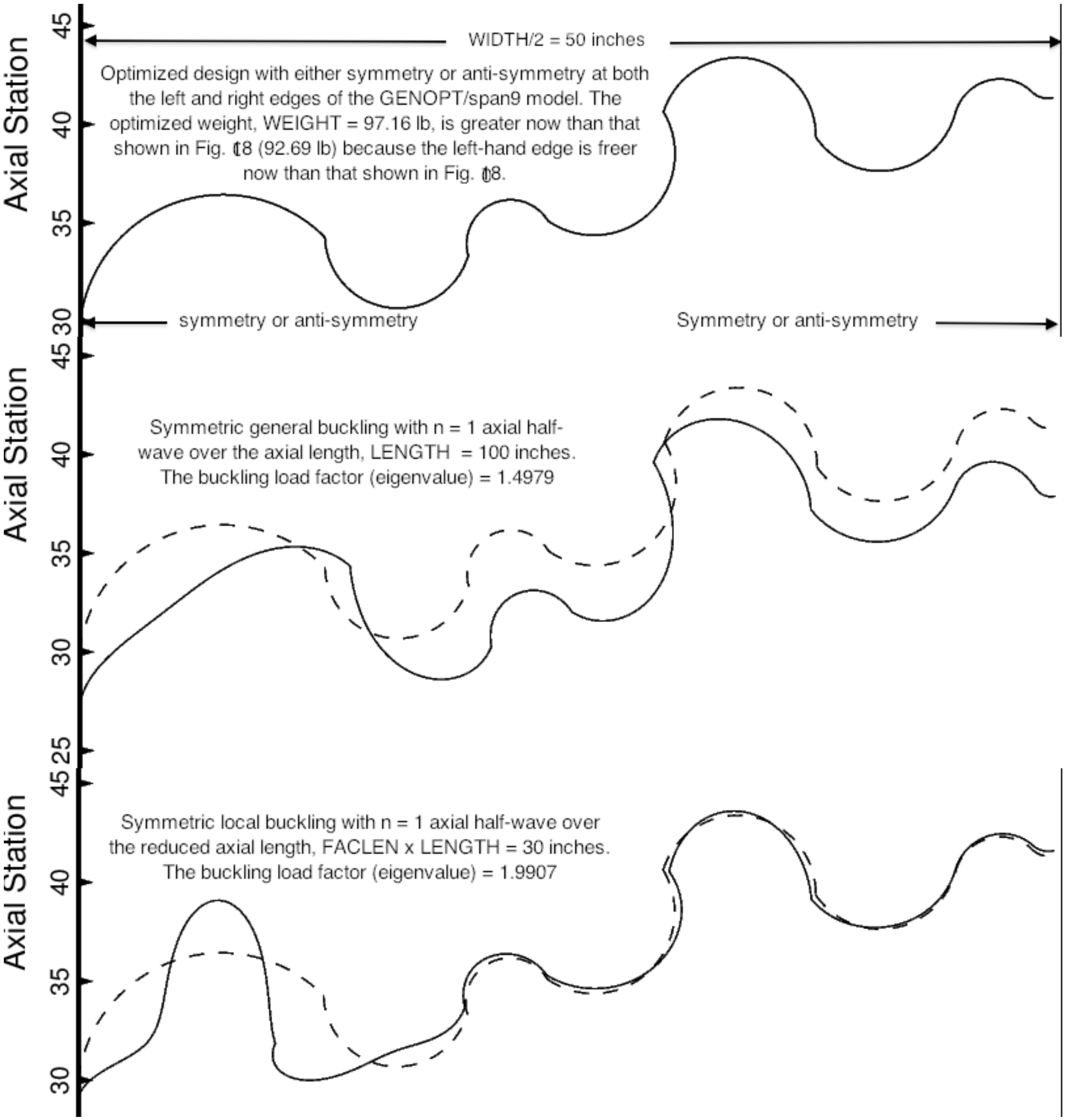


Fig. 9 **A new optimized "fold98updown" design**; general and local buckling modes and buckling load factors. **The boundary condition along the left-hand edge has been changed from "u,v,w held; rotation free" (Figs.6–8) to "symmetry or anti-symmetry" in order to simulate the behavior of a wide panel of which this section is a part.** This boundary condition is referred to as **"NEW"** in Section 4. Compare the optimized profile shown in the top frame in this figure with that displayed in Fig. 6.

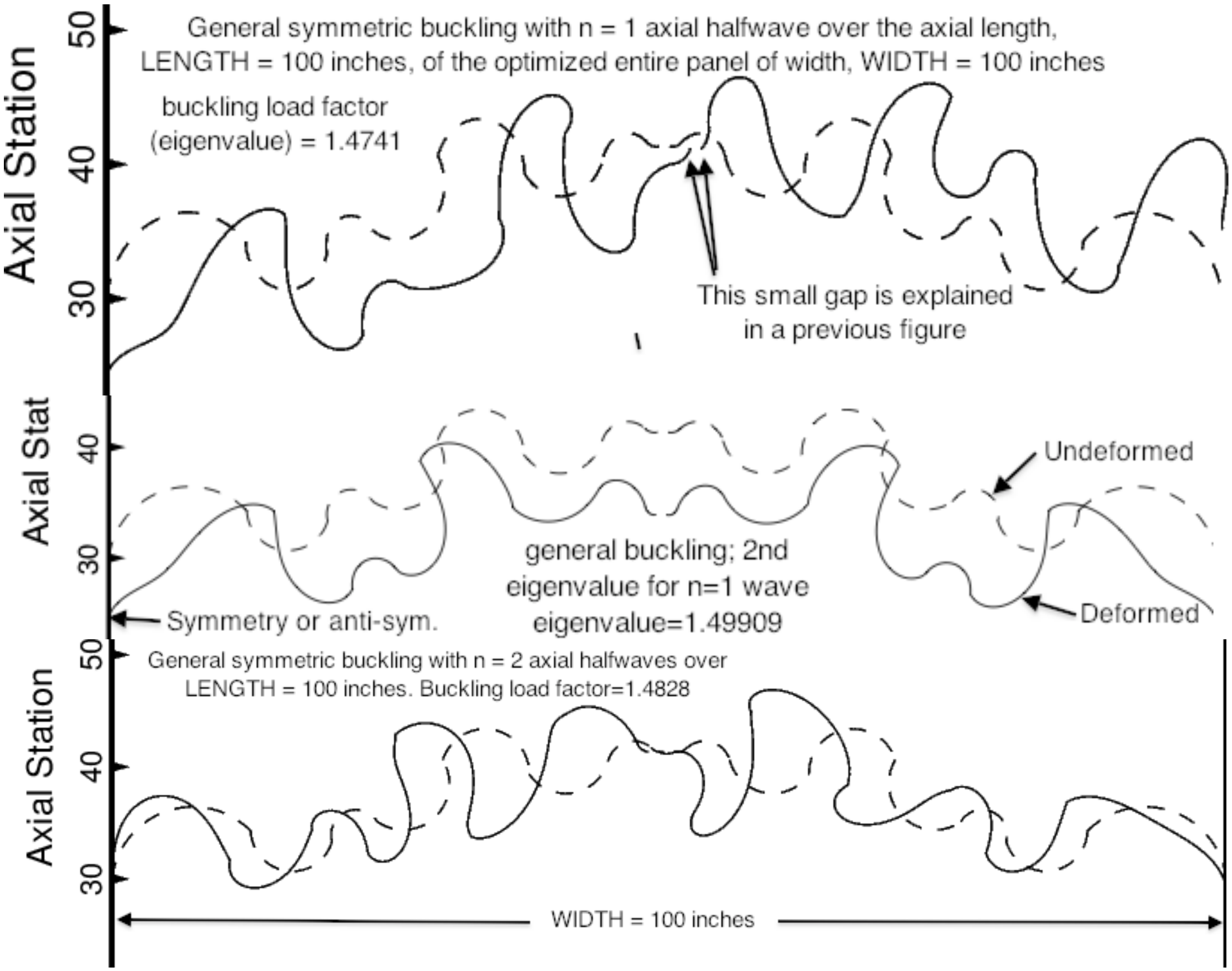


Fig. 10 **General buckling** of the optimized "fold98updown" case for which the optimized weight of the entire panel of WIDTH = 100 inches is 97.16 lb, as shown in the previous figure. Here the full panel width, WIDTH = 100 inches, is included in the new BIGBOSOR4 model. Only half of the optimized panel width is displayed in the previous figure. **NOTE: The optimization cycles are performed only for "half-width" models**. After completion of the optimization process, the behavior of that same optimized panel cross section, now with the full 100-inch width, WIDTH, included in the model, is determined by BIGBOSOR4. Notice that the 2nd eigenvalue for n = 1 for the full-width BIGBOSOR4 model (middle frame above) is very close to that shown in the middle frame of the previous figure, which is computed for the half-width model with the freer left-hand edge, that is, with symmetry/anti-symmetry boundary conditions imposed along the left-hand edge as indicated in the previous figure (referred to as **"NEW"** in Section 4) rather than with the more restrictive boundary condition, u,v,w, held and rotation free (referred to as **"OLD"** in Section 4), that is indicated in Fig. 6. In the top frame of the next figure is shown a much larger BIGBOSOR4 80-segment model of width = 5 x WIDTH = 500 inches that has 5 repeating cross section profiles, each of width, WIDTH = 100 inches and each the same as the optimized profile shown here. The phrase "General symmetric buckling" in this figure means "symmetric with respect to the longitudinal edges at x = 0 and x = WIDTH", not "symmetric at x = WIDTH/2".

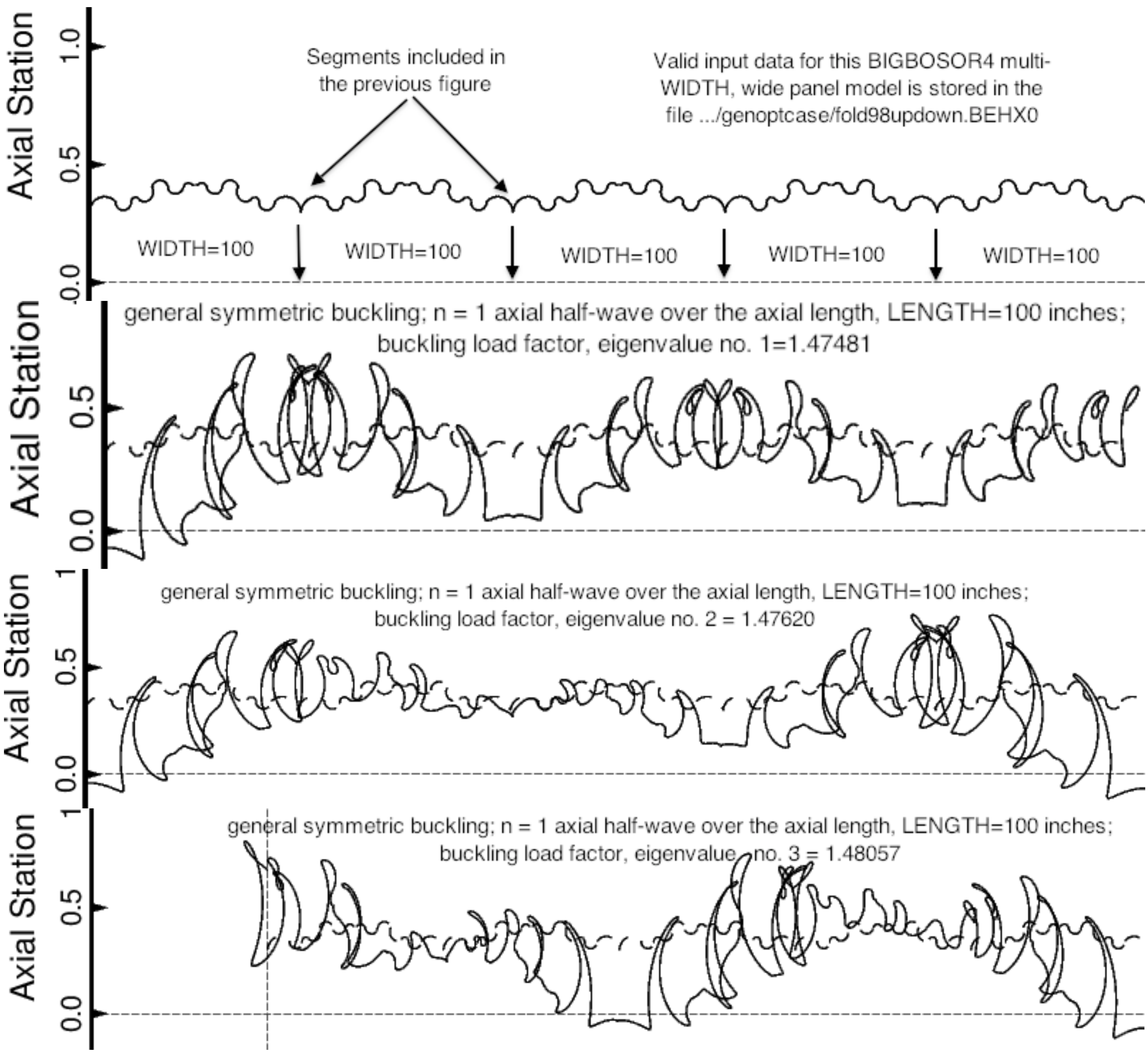


Fig. 11 Optimized **"fold98updown"** with the freer boundary conditions (referred to as **"NEW"** in Section 4) along the left-hand edge. This BIGBOSOR4 model of general symmetric buckling includes **five** full WIDTHs of 100 inches each. (The total width of the wide panel is 500 inches, with symmetry conditions applied along both the left-hand and right-hand edges.) There are 80 shell segments in this BIGBOSOR4 model. The optimum design of the panel cross section is the same as that shown in the previous two figures. The eigenvalues agree well with those from the half-width model, which is the much simpler BIGBOSOR4 model that is used for optimization of the panel cross section.

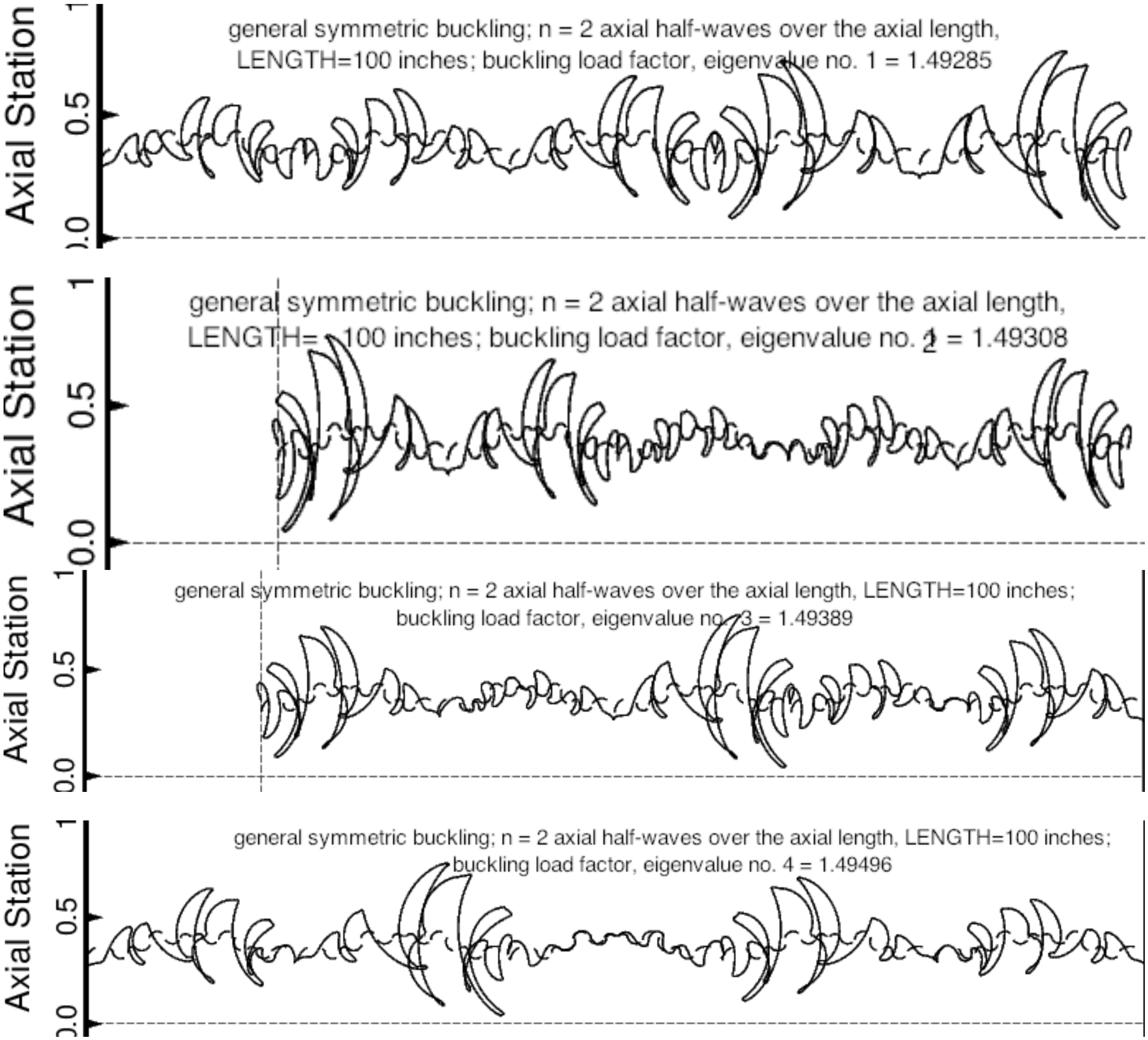


Fig. 12 Optimized **"fold98updown"** with the freer boundary conditions (referred to as **"NEW"** in Section 4) on the left-hand edge. These frames show buckling modes corresponding to n = 2 axial half-waves over the axial length, LENGTH = 100 inches. As with the previous figure, this BIGBOSOR4 model of general symmetric buckling includes **five** full WIDTHs of 100 inches each. (The total width of the wide panel is 500 inches, with symmetry conditions applied along both the left-hand and right-hand edges.) There are 80 shell segments in this model. The eigenvalues agree well with those from the half-width model, which is the much simpler BIGBOSOR4 model used for optimization of the panel cross section. Notice from this and the previous figure how the eigenvalues are closely clustered.

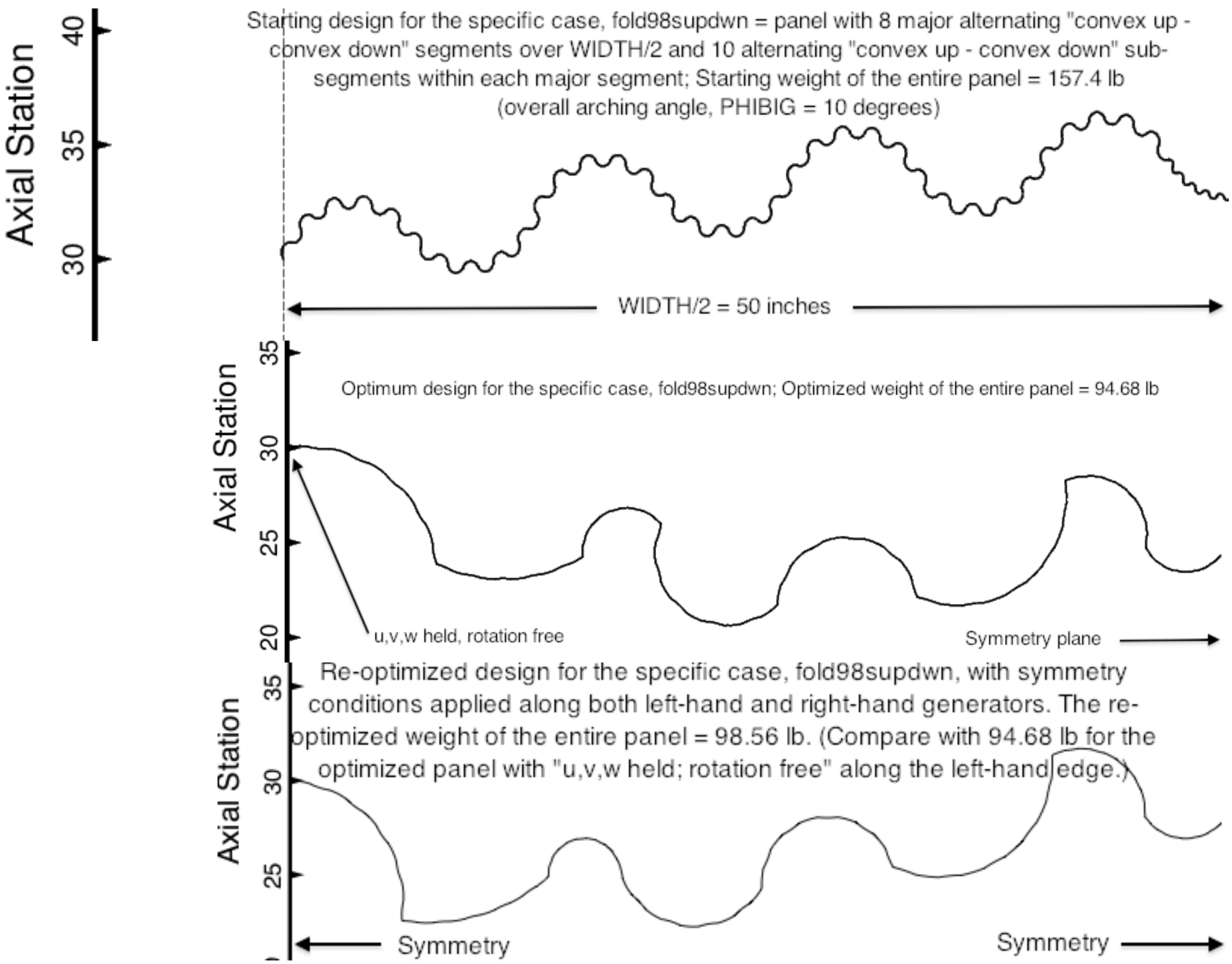


Fig. 13 Starting design and optimized designs for the specific case, **fold98supdwn (panel with sub-segments)**: **top frame =** starting design; the letter "s" in the name, fold98supdwn, indicates the presence of sub-segments; **middle frame =** optimized design with u,v,w held; rotation free along the left-hand edge (referred to as **"OLD"** in Section 4);
bottom frame = optimized design with symmetry conditions applied along the left-hand edge (referred to as **"NEW"** in Section 4).
Compare with the optimized designs of the "convex up – convex down" panels with no sub-segments shown in Figs. 6 and 9. In the optimized designs of the panel with sub-segments the amplitudes of the sub-segments are very small but not zero. In this case of alternating "convex up" and "convex down" major segments and alternating "convex up" and "convex down" sub-segments in each major segment, zero amplitude of the sub-segments is not the limiting case equivalent to a panel without sub-segments. This fact is a consequence of the "span9" formulation in which PHISUB(i), i = 1, 2, …8 (the half-angles subtended by a single sub-segment in major segment number i) are decision variables. If all the 10 sub-segments in major segment no. 1 were "convex down", all the 10 sub-segments in major segment no. 2 were "convex up", and so on, then the limiting case equivalent to a geometry with no sub-segments would have PHISUB(i) = PHISEG(i)/10, i = 1, 2, … 8.

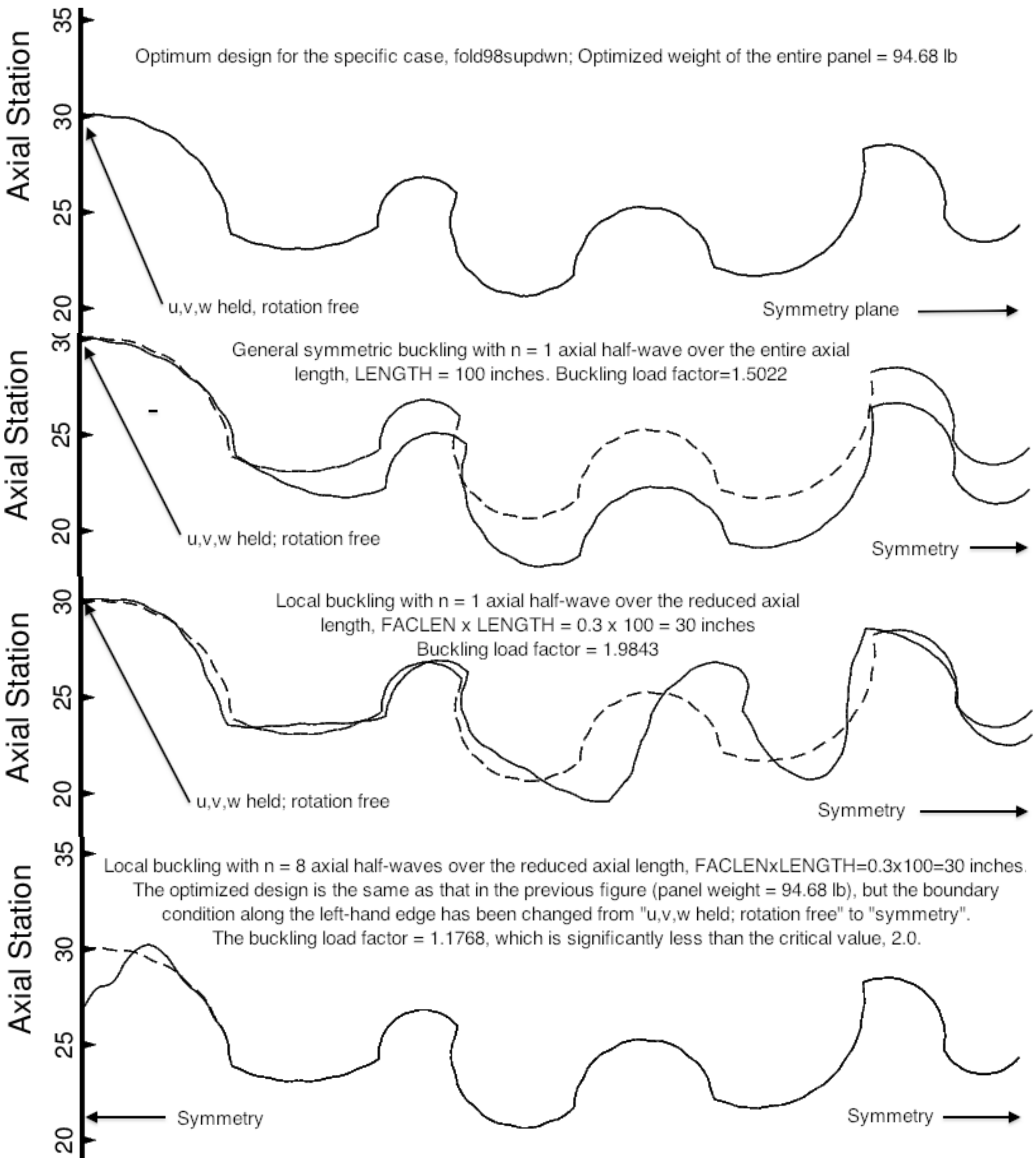


Fig. 14 **Top frame:** optimized design of **fold98supdwn (panel with sub-segments)** with left-hand boundary condition “u,v,w held, rotation free”; **2nd frame:** general buckling, **3rd frame:** local buckling; **bottom frame:** local buckling of the **same design with the boundary condition along the left-hand edge changed from “u,v,w held, rotation free”** (referred to as **“OLD”** in Section 4) **to “symmetry”** (referred to as **“NEW”** in Section 4)**.** (The purpose of the change in the boundary condition along the left-hand edge is to be able to simulate with BIGBOSOR4 the behavior of a very wide panel with repeating cross sections.)

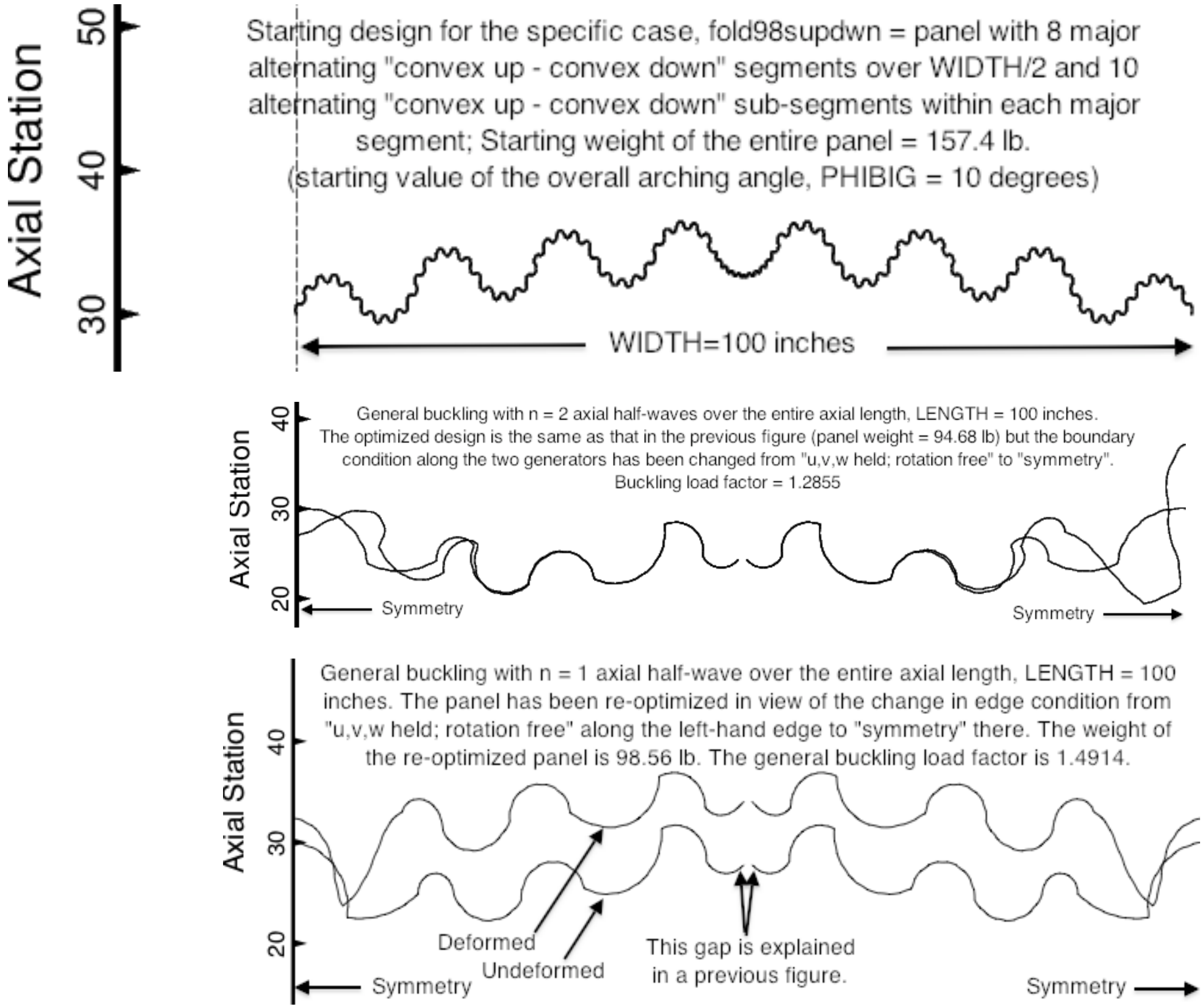


Fig. 15 **Top frame:** starting design of **fold98supdwn (entire panel width with sub-segments)**; **Middle frame:** general buckling of the panel optimized with the boundary condition along the left-hand edge set at “u,v,w held, rotation free” (referred to as **“OLD”** in Section 4) during optimization but with this left-hand boundary condition changed to “symmetry” (referred to as **“NEW”** in Section 4) after optimization; **Bottom frame:** general buckling of the **re-optimized panel** with boundary condition along the left-hand edge set at “symmetry” during optimization instead of “u,v,w held, rotation free”.

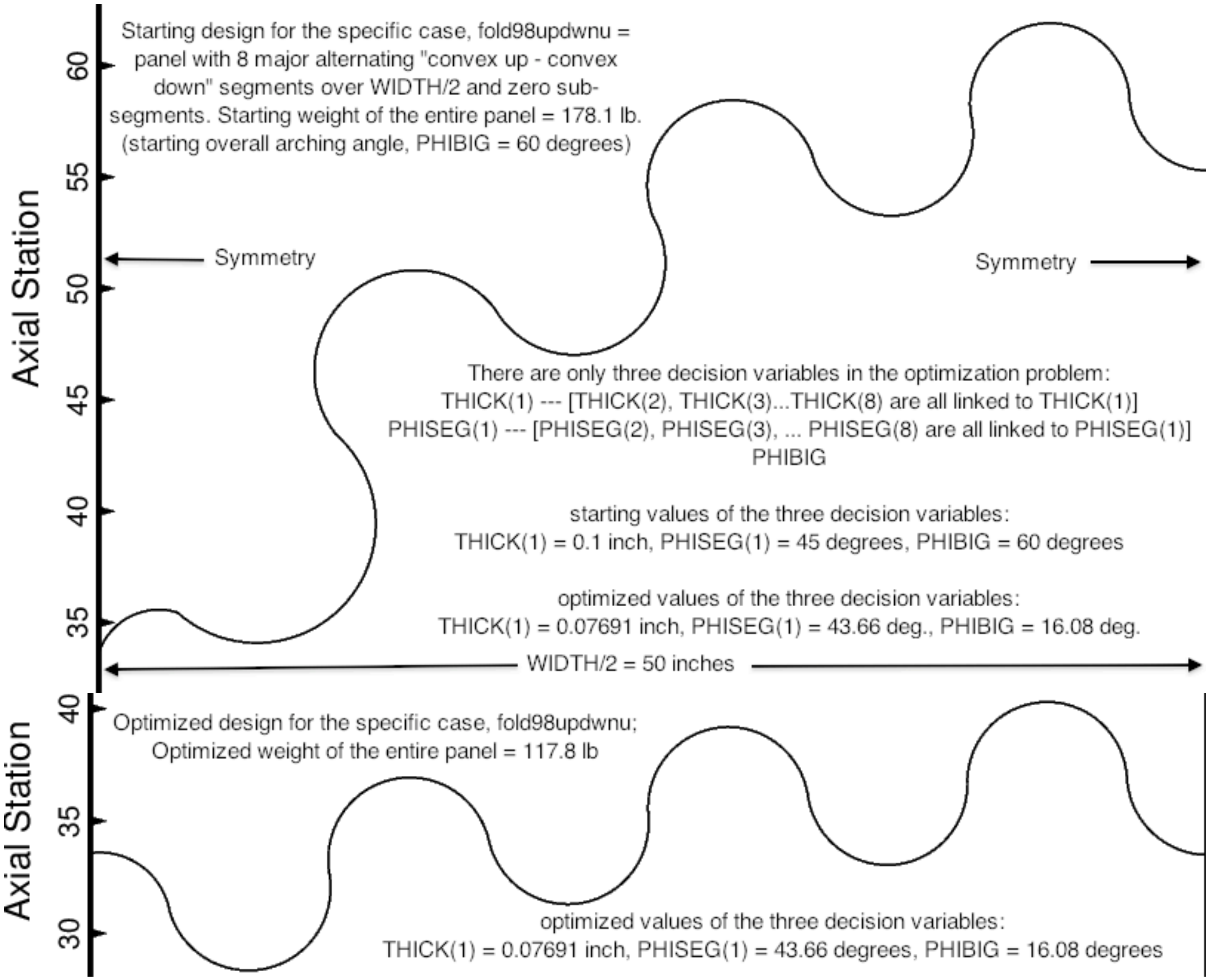


Fig. 16 Starting design and optimized design for the specific case, **fold98updwnu (panel with uniform alternating "convex up" and "convex down**" major segments, zero sub-segments, and non-zero PHIBIG): **top frame =** the starting design. The **"NEW"** (symmetry) boundary condition is used on the left-hand edge. **bottom frame =** the optimized design with symmetry conditions applied along the left-hand edge.

The purpose of this model is to compare the optimized weight of the **complex** corrugated panel shown in the top frame of Fig. 9 (in which the geometry of each major segment is different: optimized panel weight = 97.16 lb) with the optimized weight of a panel with **uniform** "convex up – convex down" major segments: optimized panel weight = 117.8 lb). NOTE: The optimized weight of a **complex** corrugated panel is significantly less (WEIGHT = 97.16 lb) as indicated in the top frame in Fig. 9 if each major segment is permitted to have a different PHISEG(i) during optimization and YPLATE(i) are decision variables, than is so in this "**uniform**" case (WEIGHT=117.8 lb) for which only THICK(1) and PHISEG(1) are decision variables and PHISEG(k), k = 2, 3, …, 8 are all linked to PHISEG(1). SUBWID(i), i = 1, 2, …, 8 and YPLATE(i), i = 1, 2, …, 9 are not decision variables.

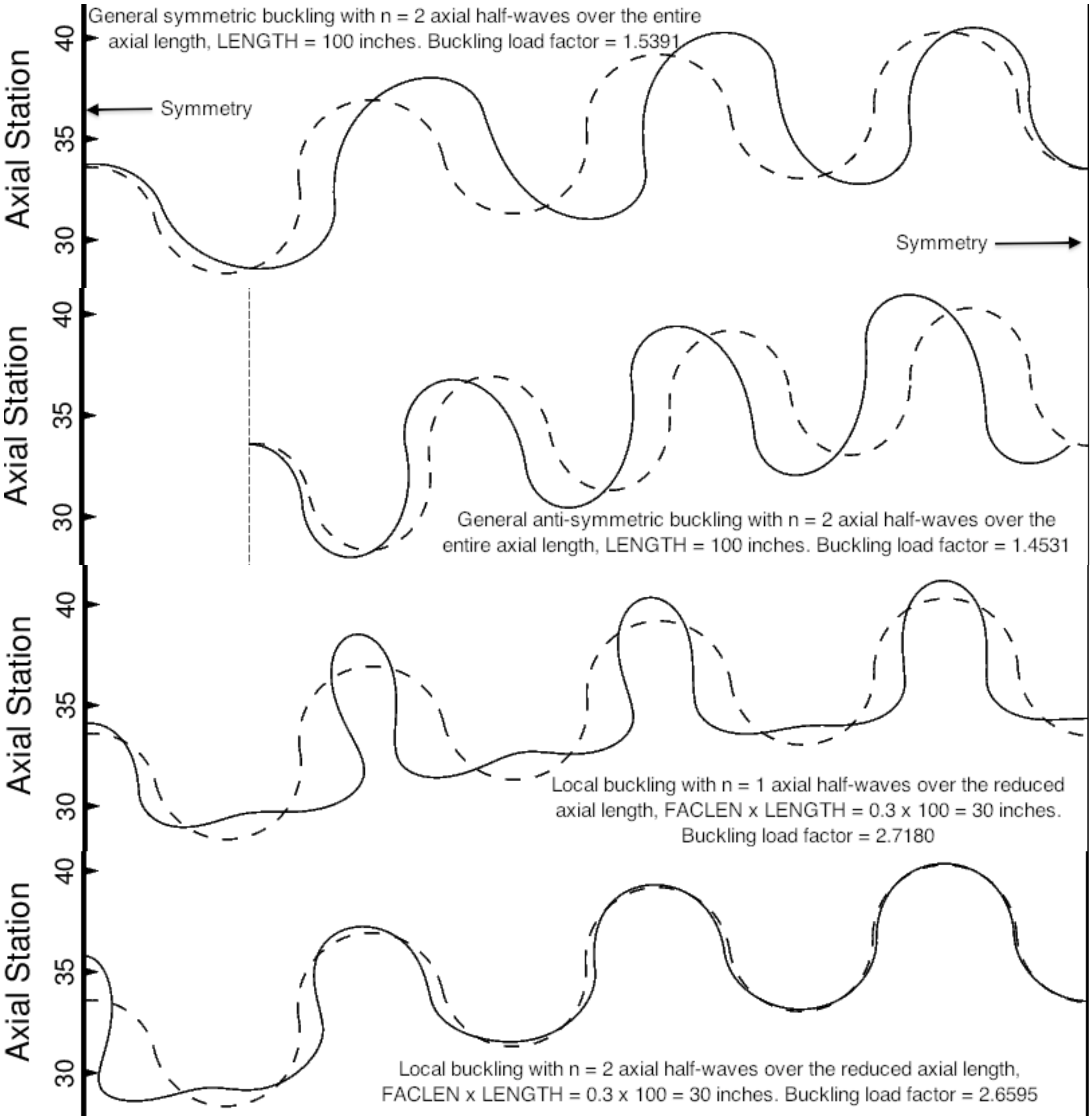


Fig. 17 **General and local buckling of the optimized specific case, fold98updwnu: panel with uniform segments.** The **"NEW"** (symmetry) boundary condition is used on the left-hand edge.

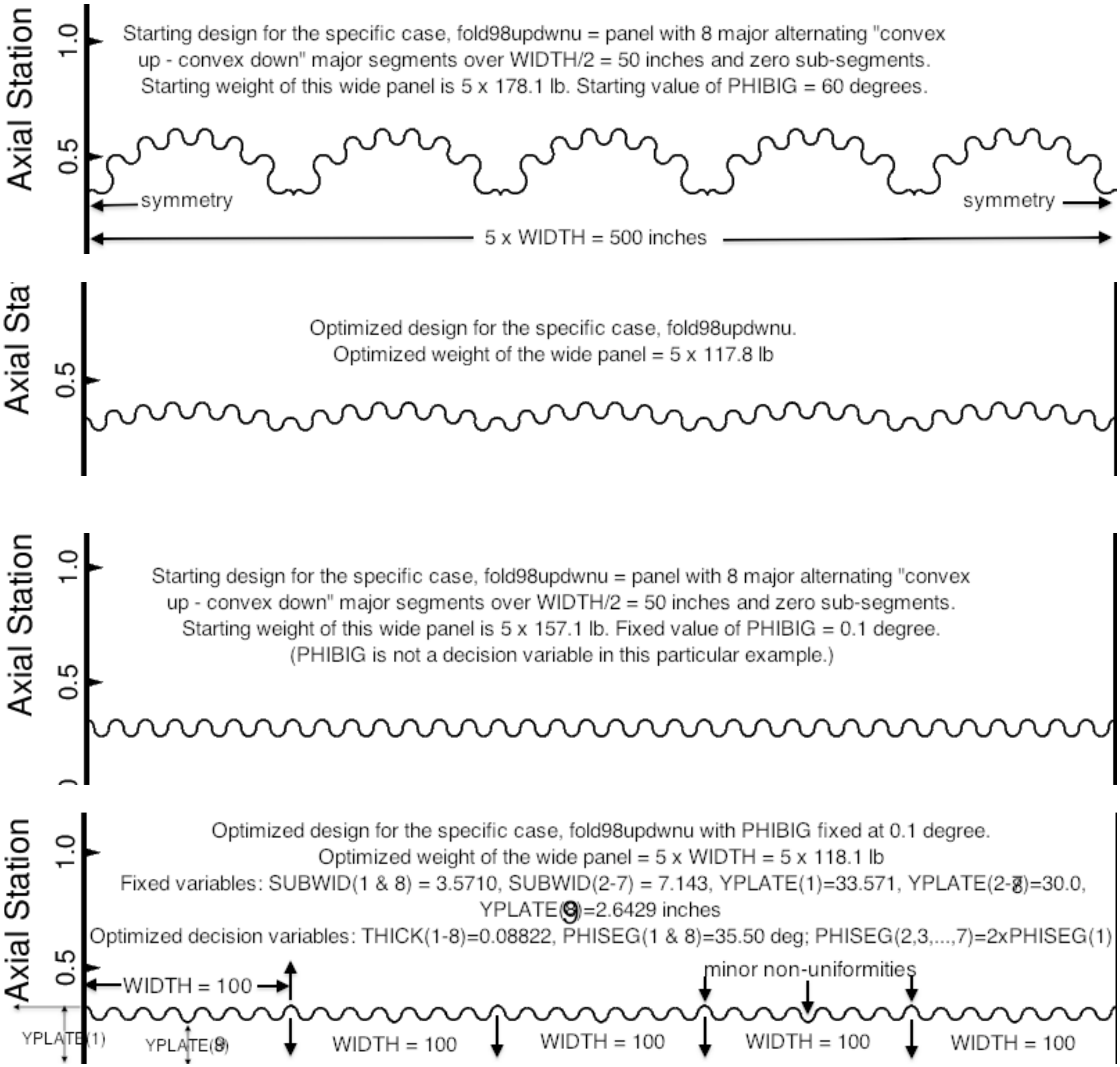


Fig. 18 Starting and optimum designs for the specific case, **fold98updwnu (uniform major segments)**:
Top two frames: PHIBIG is a decision variable; top frame PHIBIG = 60 deg.; 2nd frame PHIBIG=16.08 deg.
Bottom two frames: PHIBIG is **not** a decision variable and is fixed at 0.1 degree (essentially zero).
The minor nonuniformities (corrugations with slightly greater amplitude than the others in the bottom frame) result from a somewhat too-high value of YPLATE(1) and too-low value of YPLATE(9) compared to YPLATE(2), YPLATE(3), …, YPLATE(8) = 30 inches. [YPLATE(i), i=1, 2,…,9, are not decision variables.]

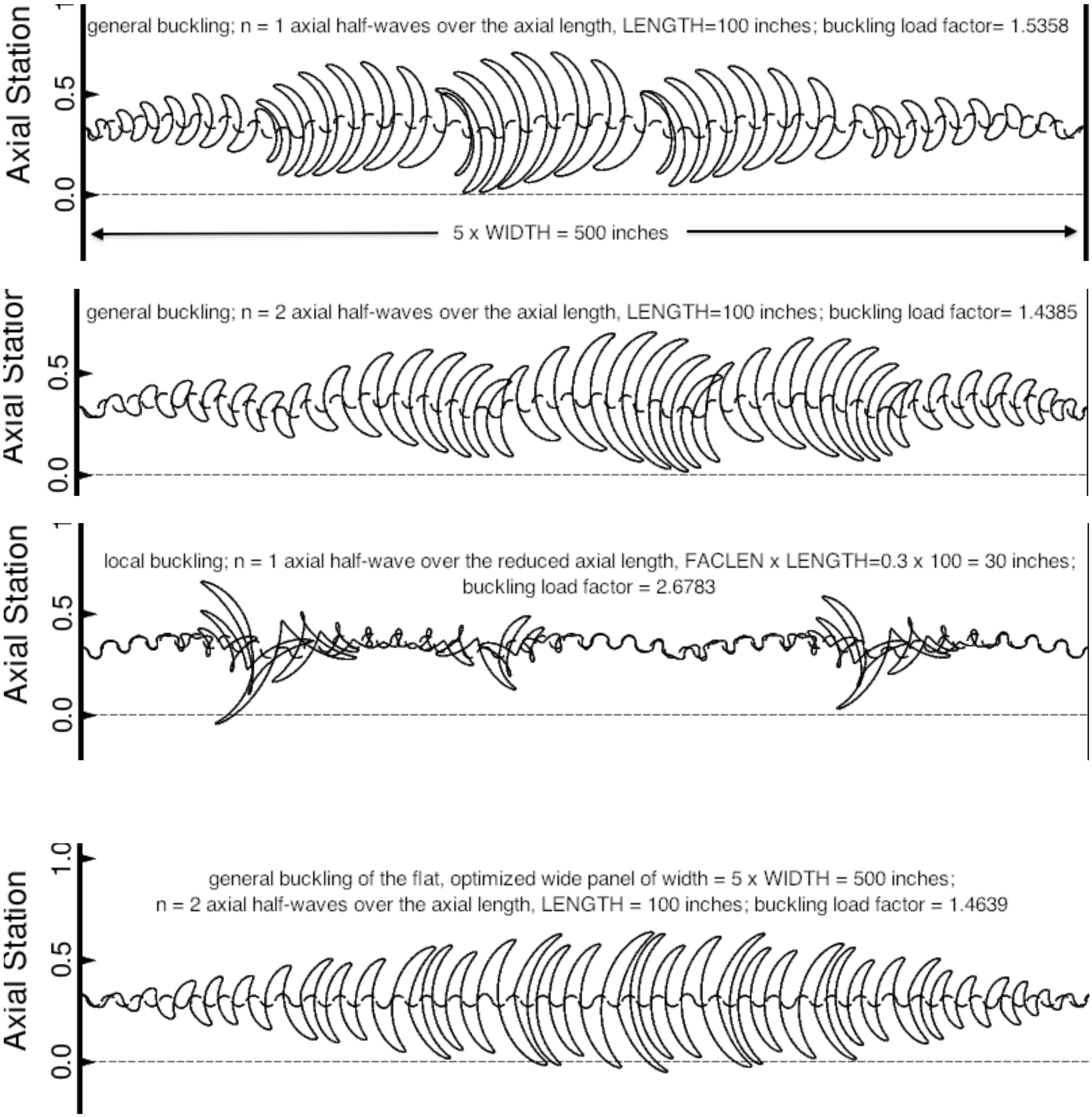
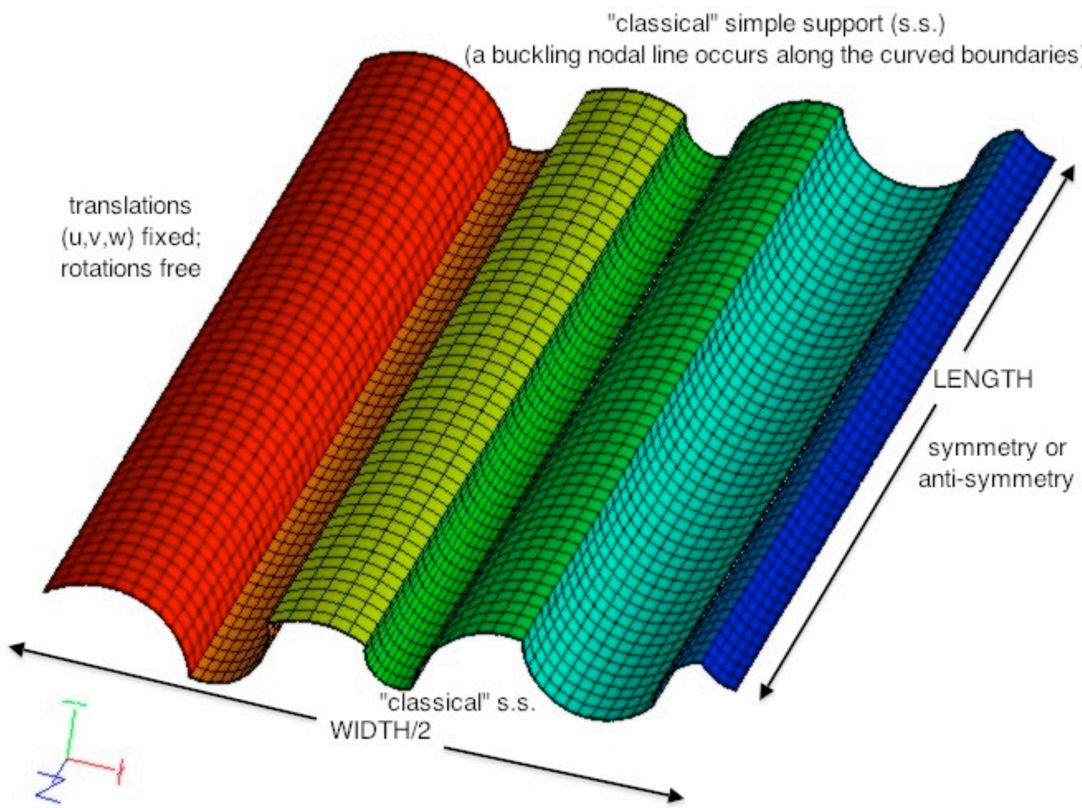
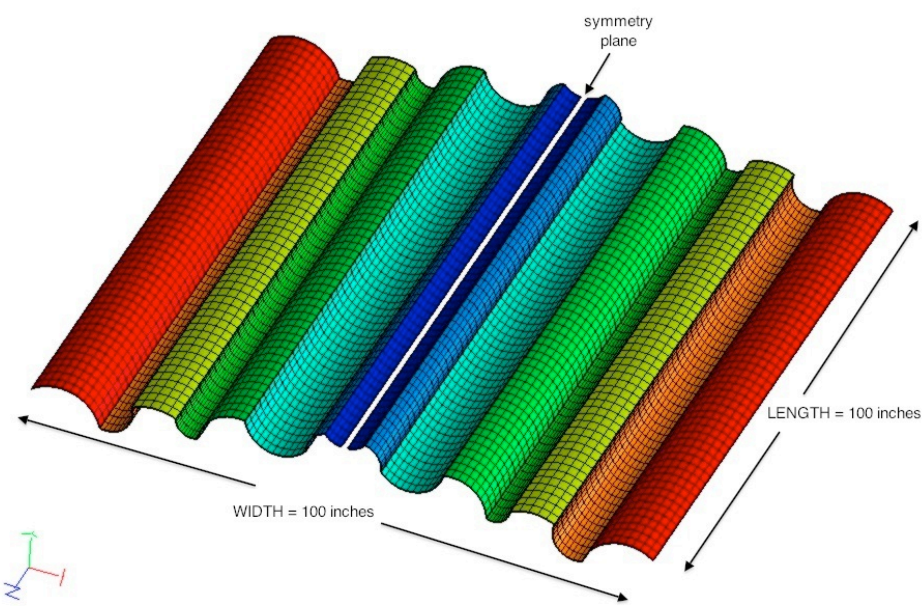


Fig. 19 **Buckling from BIGBOSOR4** of the optimized **curved** (top three frames; PHIBIG=16.08 degrees) and **"flat"** (bottom frame; PHIBIG=0.10 degree) "**uniform**" (specific case = **fold98updwnu**) wide panels shown in frames 2 and 4 in the previous figure.



(a) STAGS "half-width" model of the corrugated panel optimized by GENOPT/span9/BIGBOSOR4



(b) STAGS "whole-width" model of the same optimized corrugated panel

Fig. 20 **STAGS finite element models of the previously optimized specific case called "fold98updown", the optimized cross-section profiles of which are displayed in Figs. 2 and 6. ("OLD" boundary conditions)**

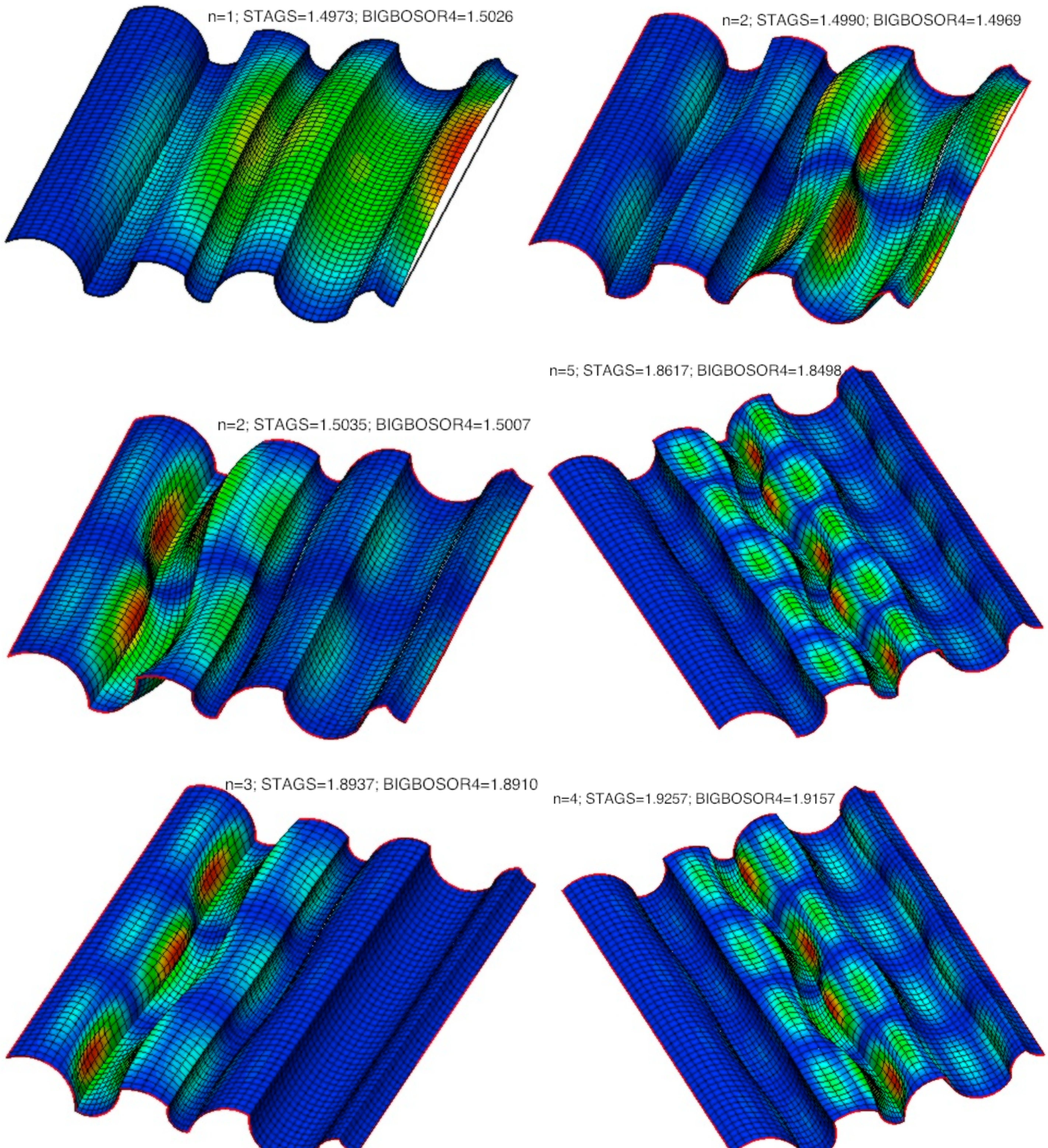


Fig. 21 **First six buckling modes and load factors from STAGS** that are **symmetric** at the symmetry plane. Predictions from BIGBOSOR4 agree very well with those from the STAGS model shown in Fig. 20(a).

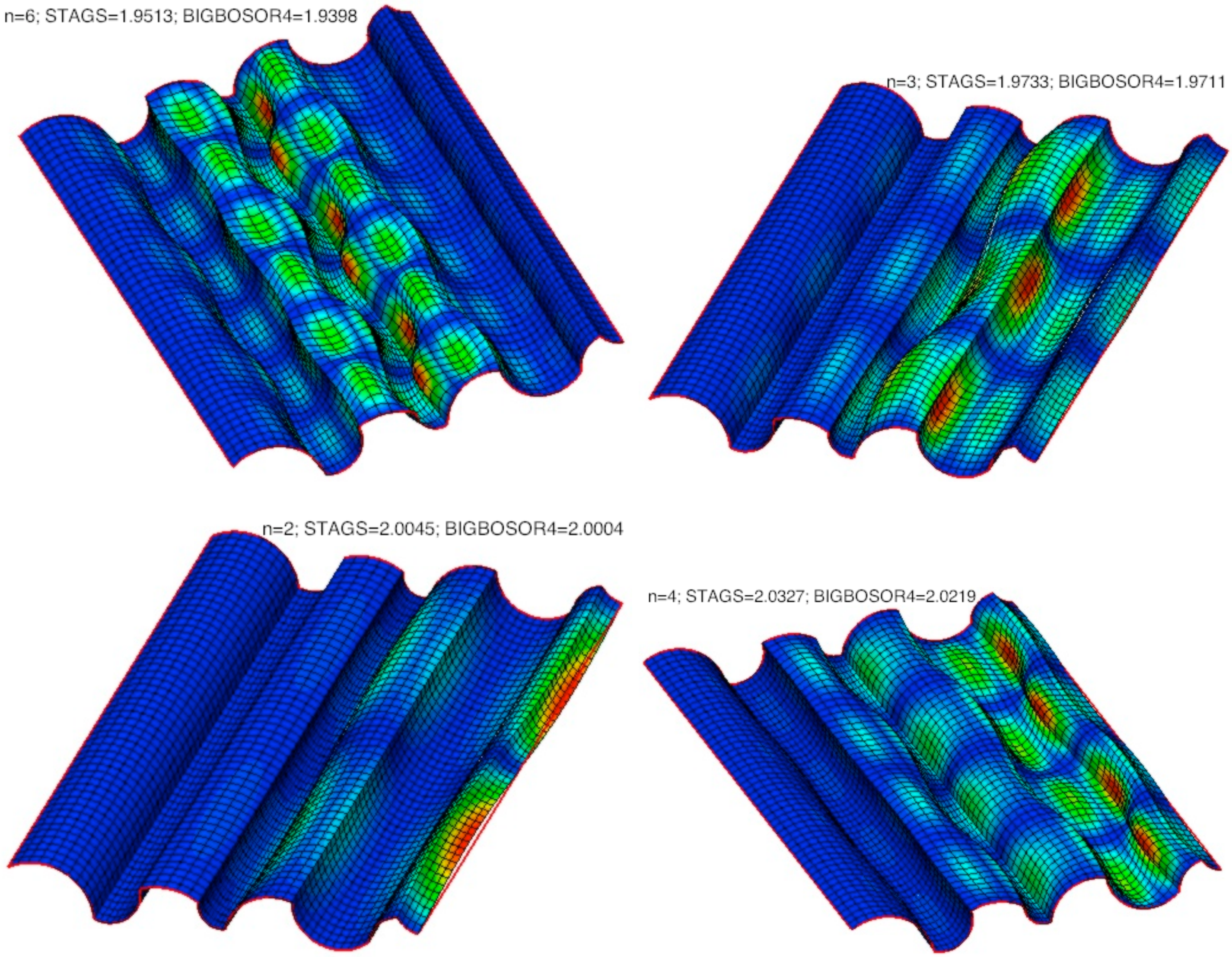


Fig. 21 (continued) Buckling modes 7 – 10 and load factors from STAGS that are **symmetric** at the symmetry plane. Predictions from BIGBOSOR4 agree very well with those from the STAGS model shown in Fig. 20(a). (“OLD” boundary conditions)

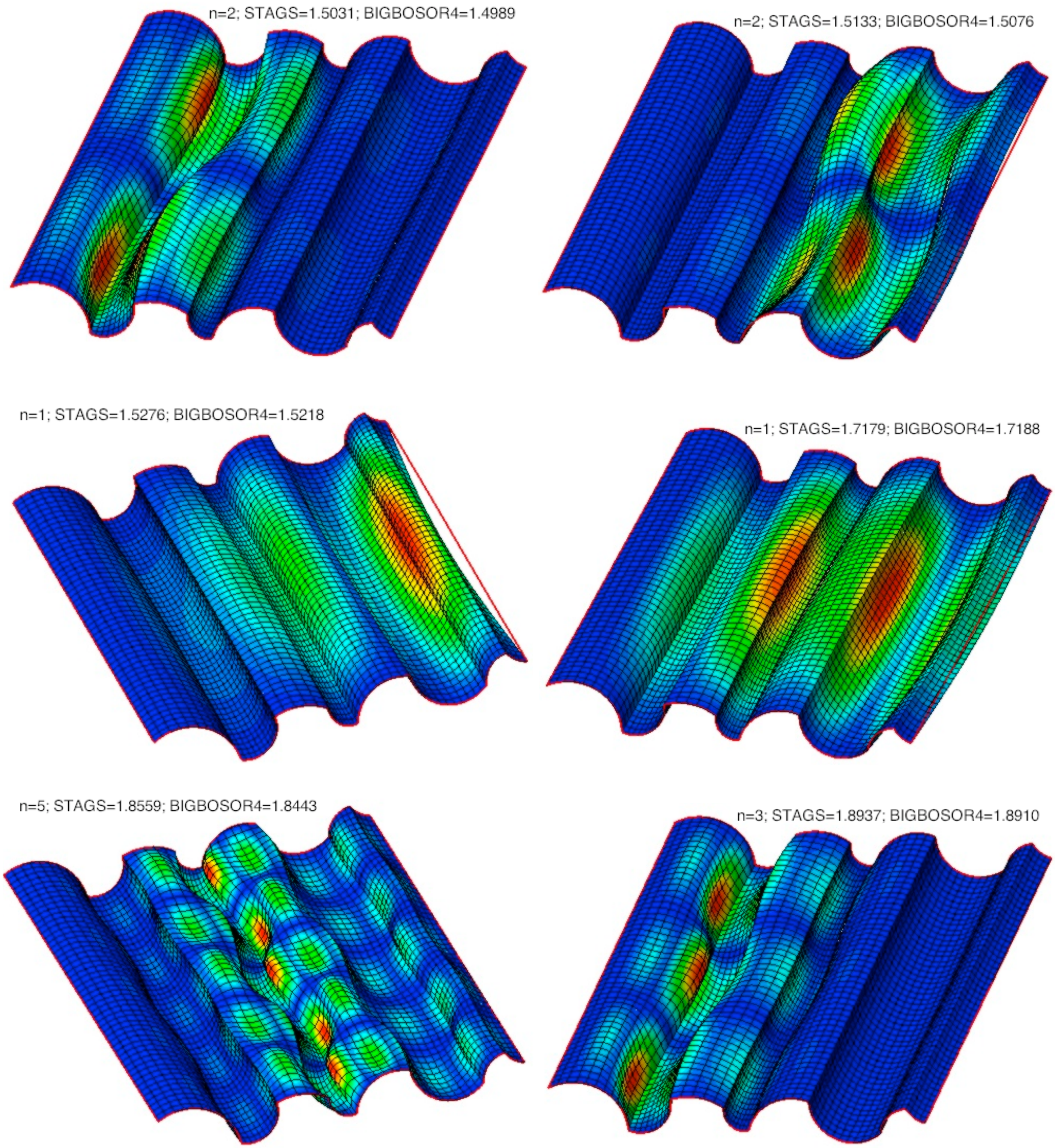


Fig. 22 **First six buckling modes and load factors from STAGS** that are **anti-symmetric** at the symmetry plane. Predictions from BIGBOSOR4 agree very well with those from the STAGS model shown in Fig. 20(a).

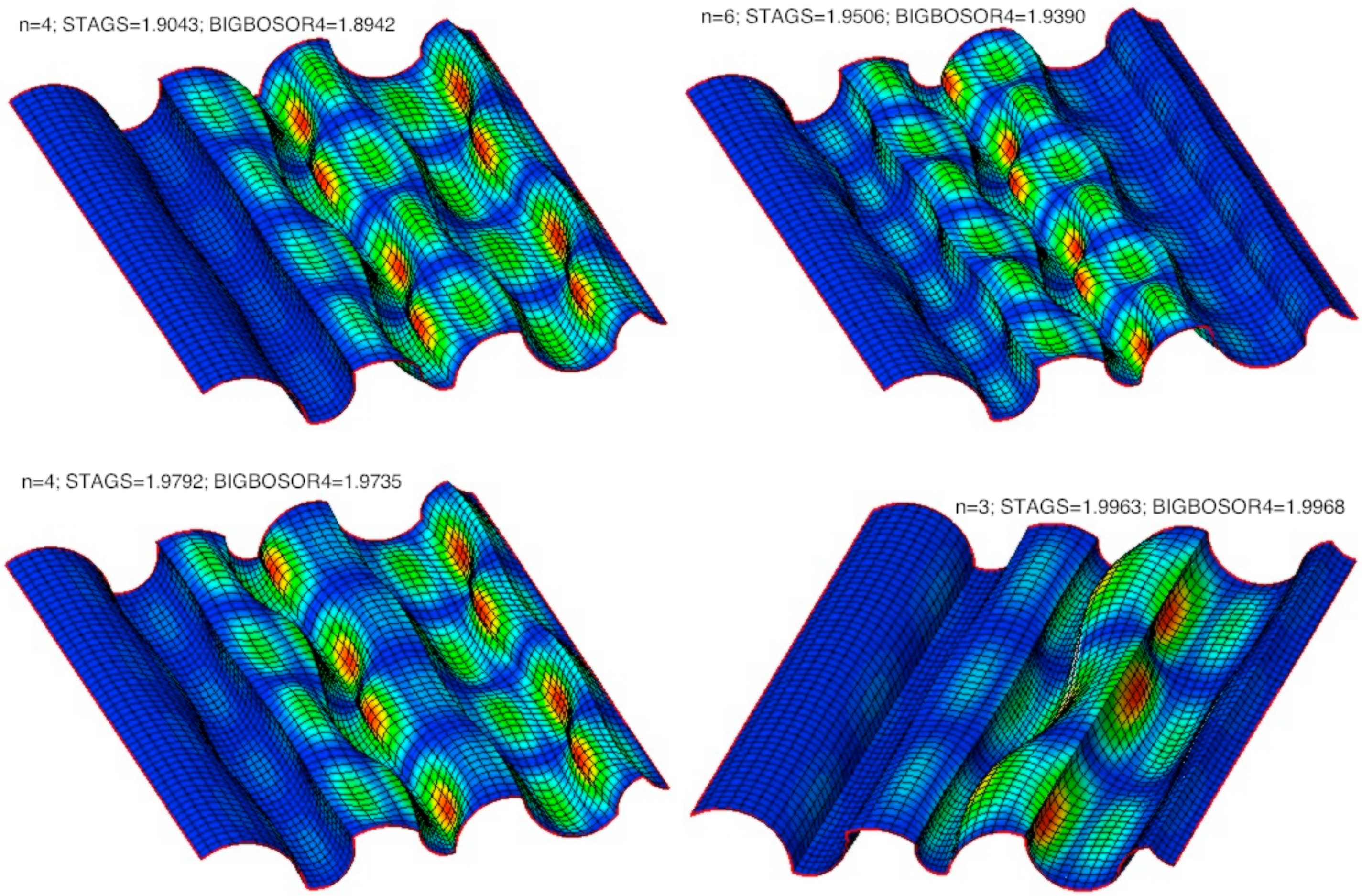


Fig. 22 (continued) Buckling modes 7 – 10 and load factors from STAGS that are **anti-symmetric** at the symmetry plane. Predictions from BIGBOSOR4 agree very well with those from the STAGS model shown in Fig. 20(a). ("**OLD**" boundary conditions)

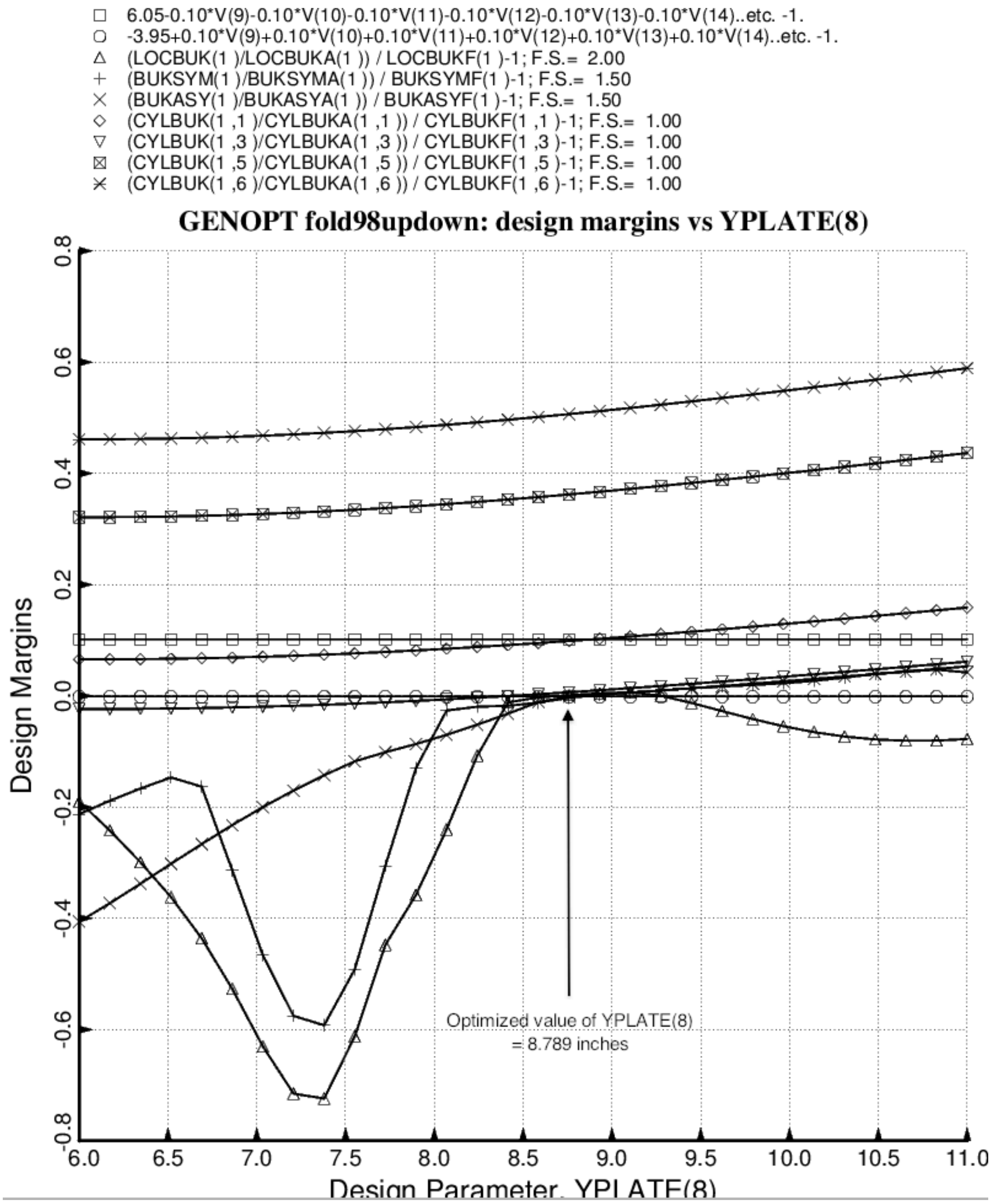


Fig. 23a **Sensitivity of the optimized design of the specific case called "fold98updown"** to variation of the decision variable, YPLATE(8). The optimized design of "fold98updown" is listed in Table 3 and the cross section of half the width of the optimized panel is shown in Figs. 2 and 6. ("**OLD**" boundary conditions)

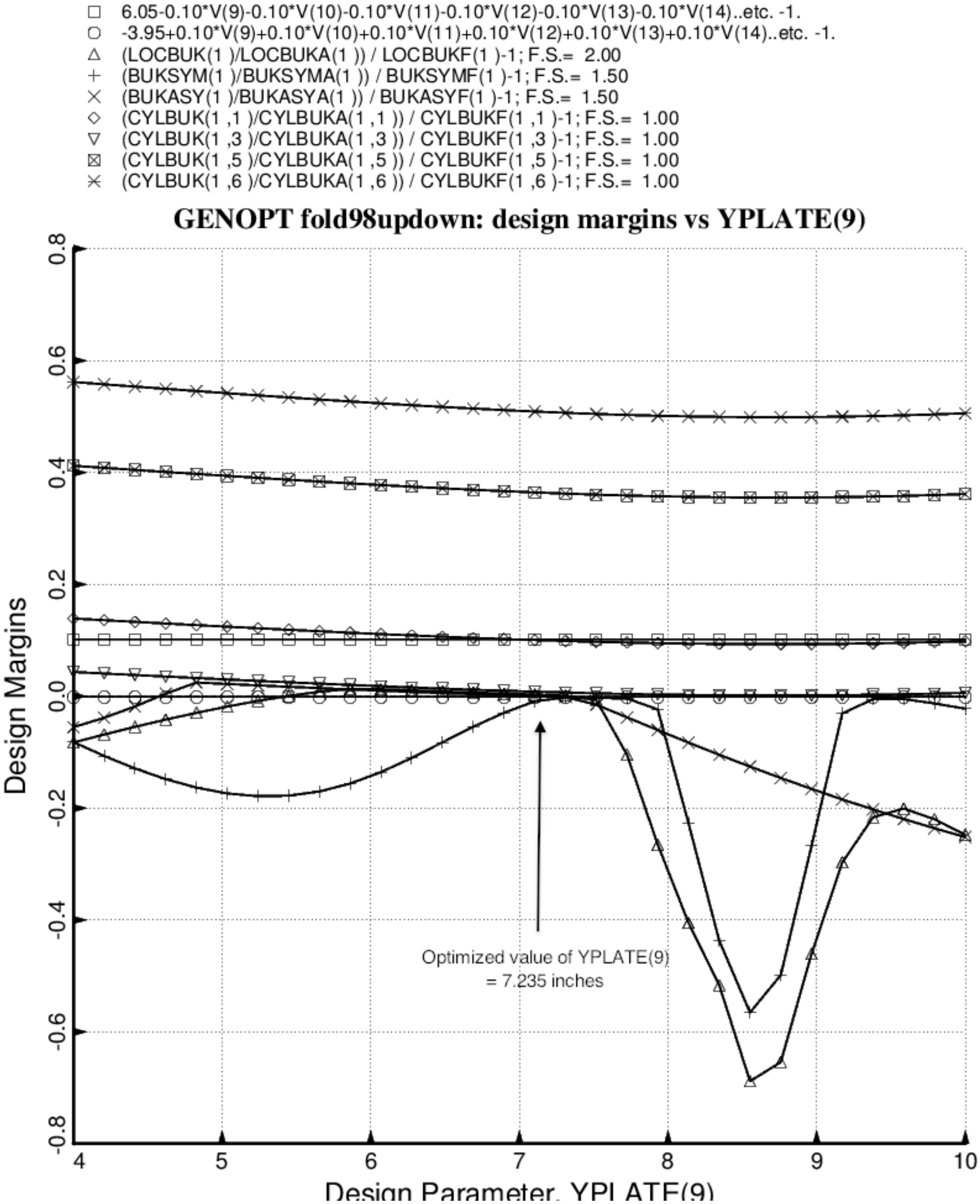
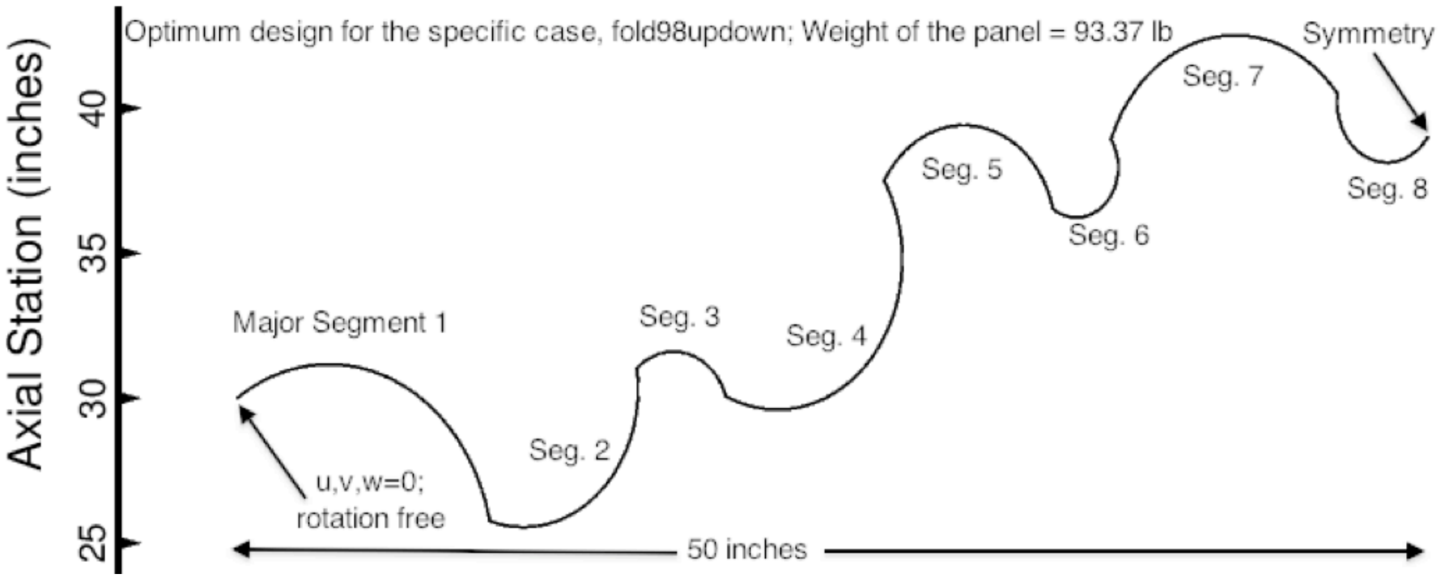
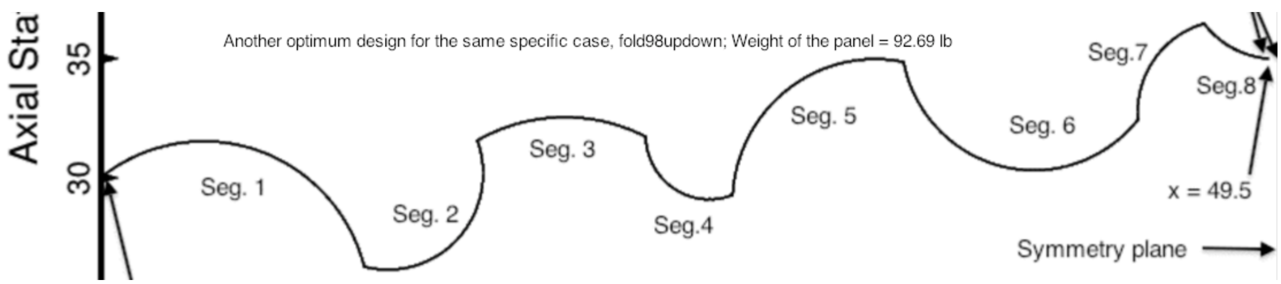


Fig. 23b **Sensitivity of the optimized design of the specific case called "fold98updown"** to variation of the decision variable, YPLATE(9). The optimized design of "fold98updown" is listed in Table 3 and the cross section of half the width of the optimized panel is shown in Figs. 2 and 6. ("**OLD**" boundary conditions)



(a) A FEASIBLE optimum design found in May 2013. This optimum design is still valid. The optimized WEIGHT = 93.37 lb.



(b) Another FEASIBLE optimum design found in July 2013 (The same optimum design is shown in Figs. 2 and 6.) The optimized WEIGHT = 92.69 lb.

Fig. 24. **Two equally valid FEASIBLE optimum designs of the specific case called "fold98updown"** ("**OLD**" boundary conditions)**.** The boundary conditions are the same in (a) and (b). The optimized panel cross sections shown here are significantly different each other, yet the optimized weights of the entire panels of WIDTH=100 inches are only slightly different: 93.37 lb in the top frame versus 92.69 lb in the bottom frame. There probably exist many quite different optimum designs with weights in the range 91 lb < WEIGHT < 98 lb.

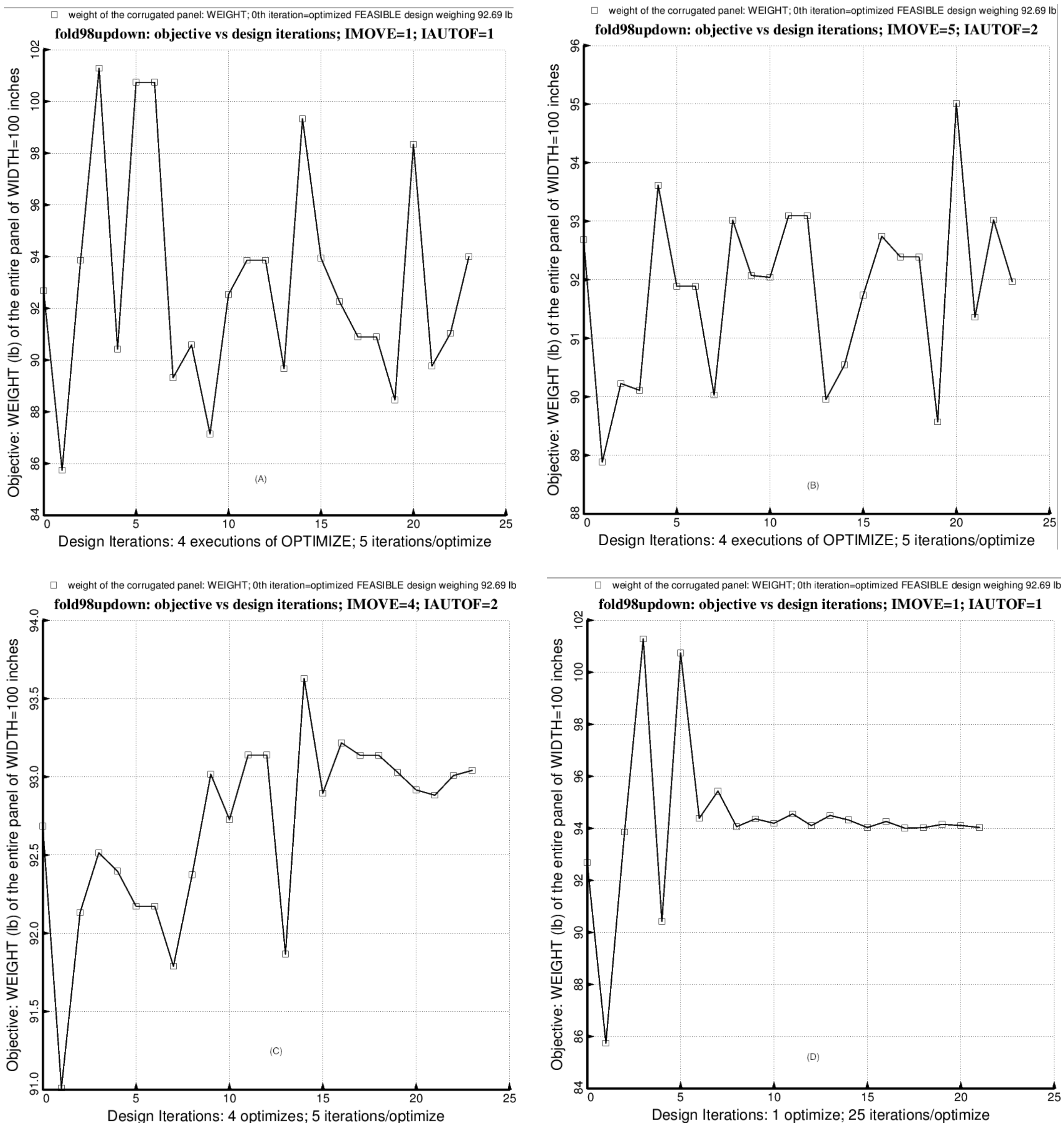


Fig. 25a **Objective** (WEIGHT of the entire panel) **versus Design Iterations** for 4 strategies in MAINSETUP:
(A) Four successive executions of OPTIMIZE with five iterations per OPTIMIZE with IMOVE = 1
(B) Four successive executions of OPTIMIZE with five iterations per OPTIMIZE with IMOVE = 5
(C) Four successive executions of OPTIMIZE with five iterations per OPTIMIZE with IMOVE = 4
(D) One executions of OPTIMIZE with 25 iterations per OPTIMIZE with IMOVE = 1

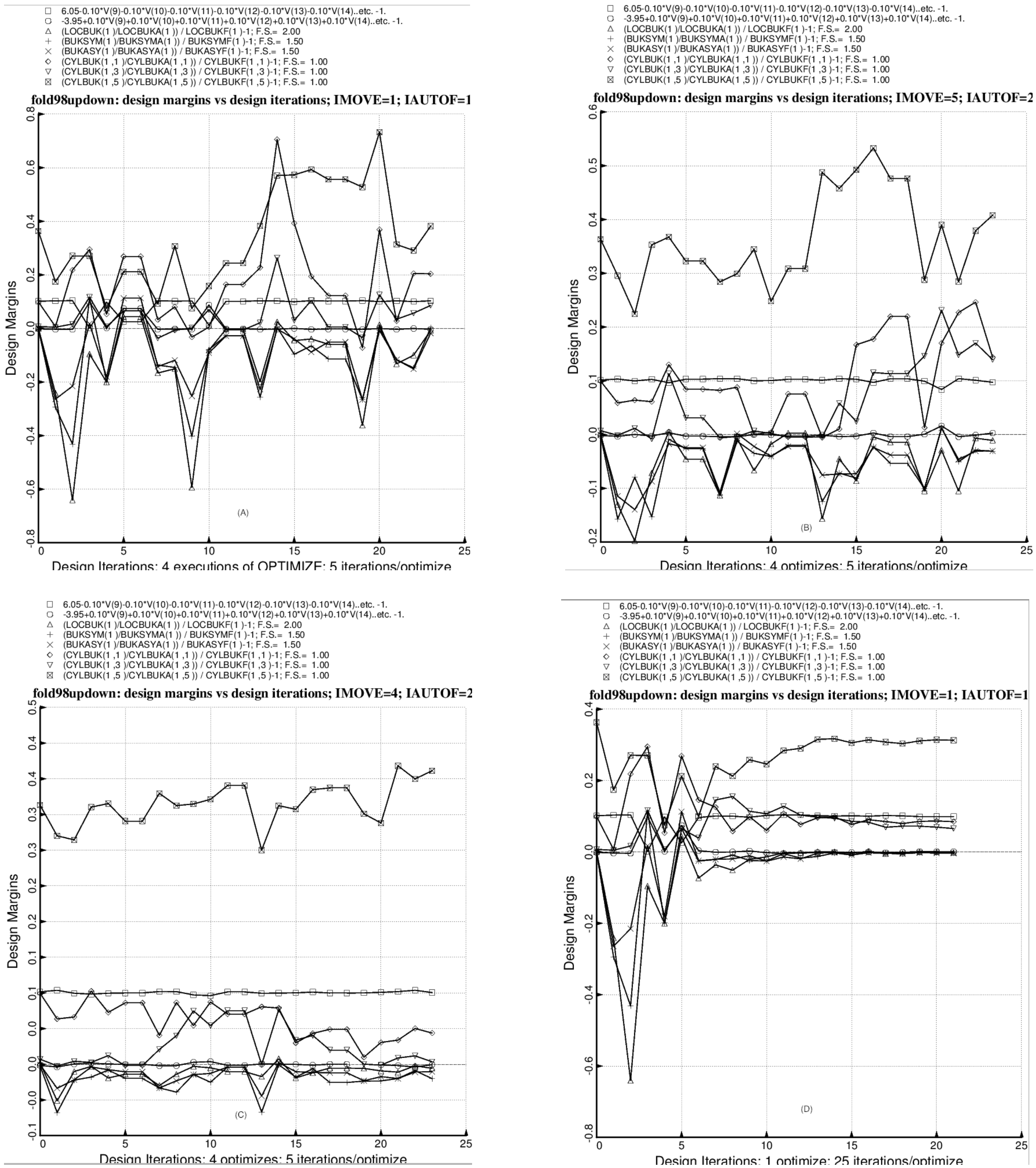


Fig. 25b **Design margins versus Design Iterations for 4 strategies in MAINSETUP**:

(A) Four successive executions of OPTIMIZE with five iterations per OPTIMIZE with IMOVE = 1

(B) Four successive executions of OPTIMIZE with five iterations per OPTIMIZE with IMOVE = 5

(C) Four successive executions of OPTIMIZE with five iterations per OPTIMIZE with IMOVE = 4

(D) One executions of OPTIMIZE with 25 iterations per OPTIMIZE with IMOVE = 1

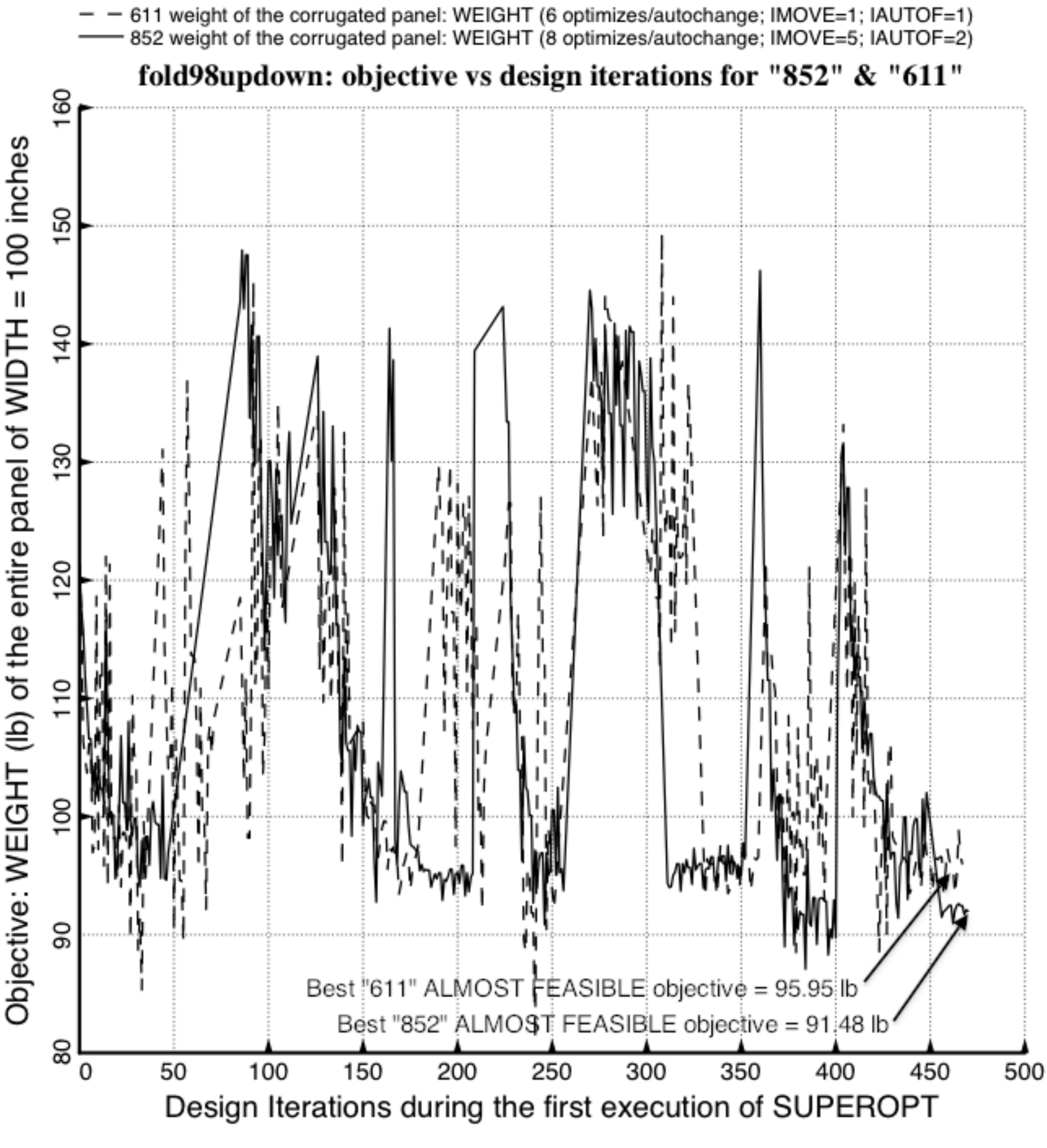


Fig. 26 **Comparison of evolution of the objective from two strategies** selected by the End user in MAINSETUP, the “611” strategy (dashed) and the “852” strategy (solid).

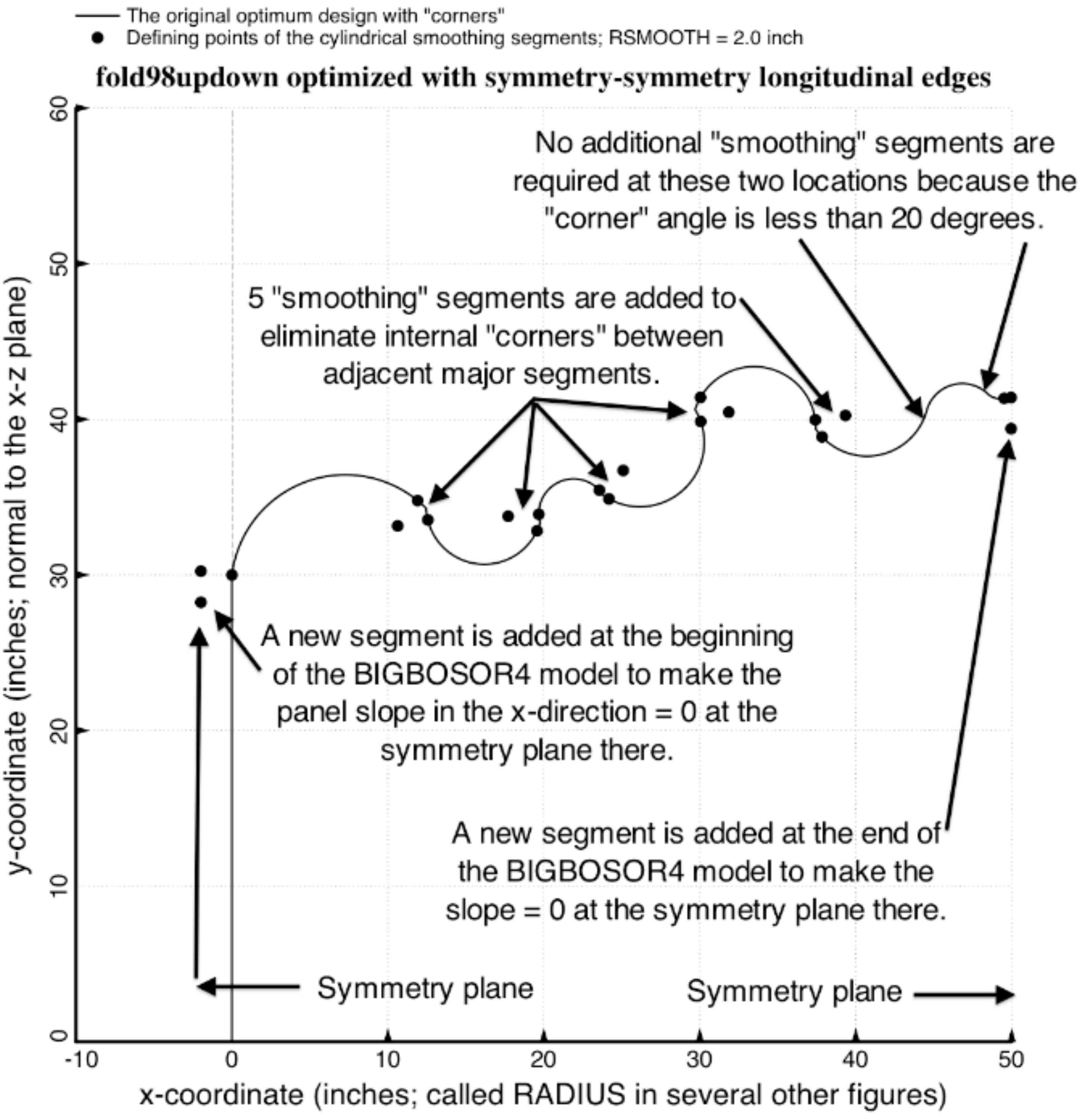


Fig. 27 The optimized specific case, fold98updown: **Solid line =** the same optimized corrugated panel profile as that shown in the top frame of Fig. 9. **Seven sets of three points each = "smoothing"** segment center of curvature, point at the beginning of the **smoothing** segment and point at the end of the **smoothing** segment.

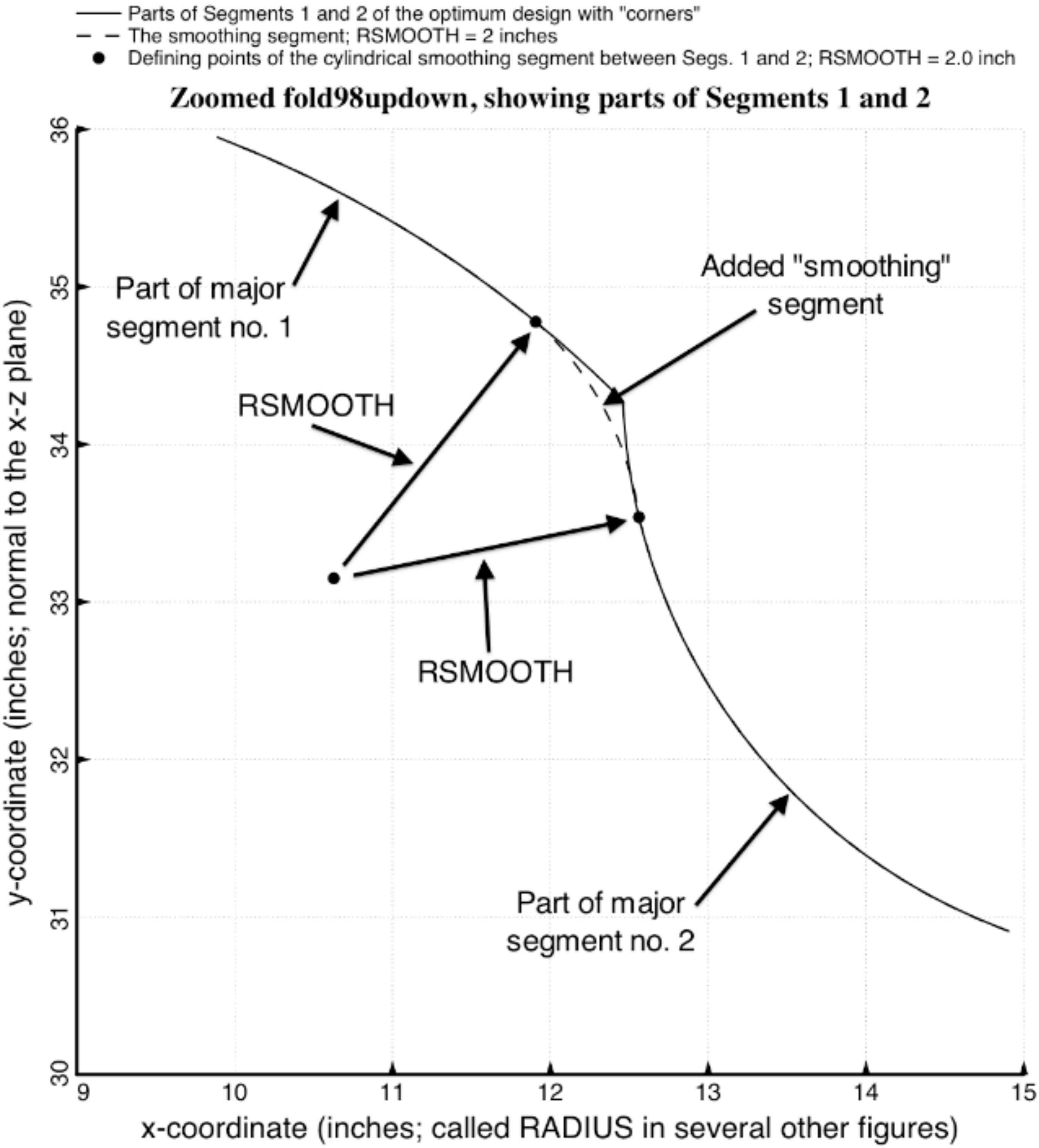


Fig. 28 **"Zoomed" view** of the smoothing segment between major segments 1 and 2 shown in the previous fig.

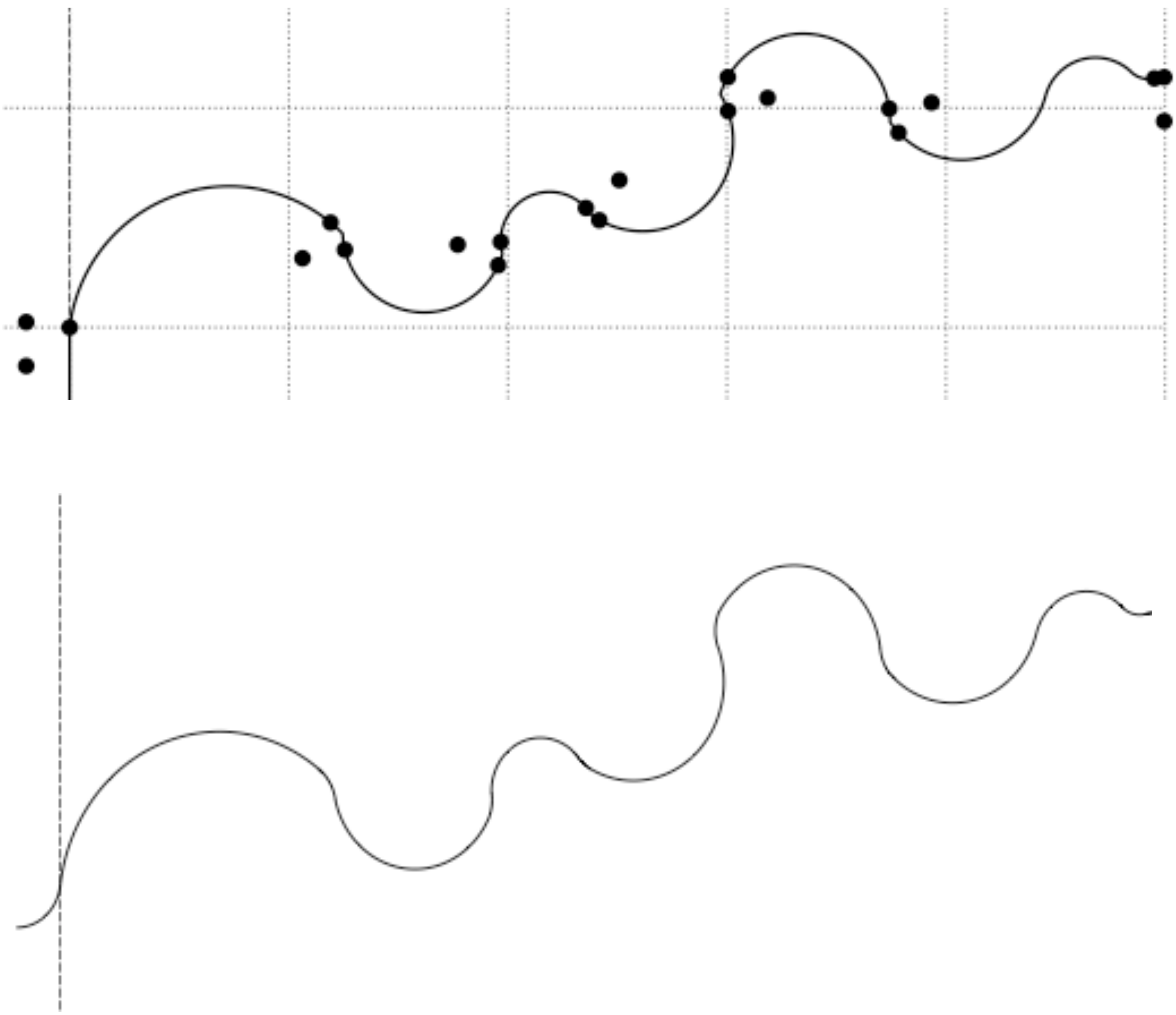


Fig. 29 **Smoothing the profile for the optimized specific case called “fold98updown”:**
Top frame: Optimized panel cross-section profile shown also in Figs 9 and 27 (before “smoothing”).
Bottom frame: The same profile with “smoothing” introduced at the left-hand and right-hand edges and between the adjacent major segments for which the “corner” angle (discontinuous slope in the width direction) is greater than 20 degrees. The optimized profile with “corners” (top frame in Fig. 9 and top frame in this figure) is determined with symmetry conditions imposed along both the left-hand and right-hand longitudinal edges (“**NEW**” boundary conditions described in Section 4). In this case no further optimization was carried out with use of the “smoothed” BIGBOSOR4 model. The profile shown in the bottom frame is the same as that shown in the top frame except that the small “smoothing” cylindrical segments have been introduced at the locations indicated by the seven sets of three points each shown in the top frame. The radii of all the added “smoothing” cylindrical segments are the same and equal to RSMOOTH = 2.0 inches in this particular example.

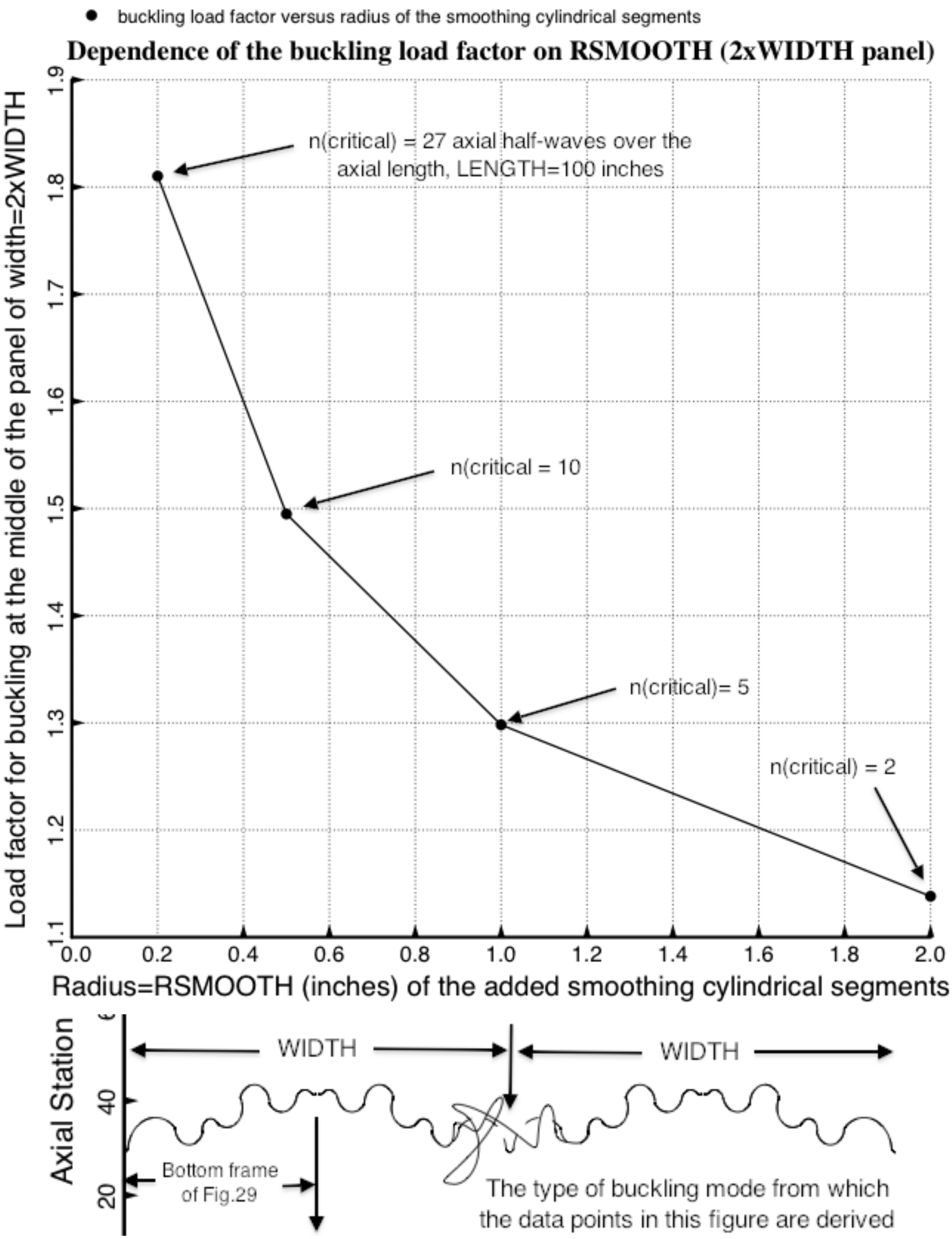


Fig. 30 Sensitivity of the critical buckling load factor of a "smoothed" optimized panel cross-section profile to the radius, RSMOOTH, of the added little cylindrical segments that eliminate the "corners" between segments.

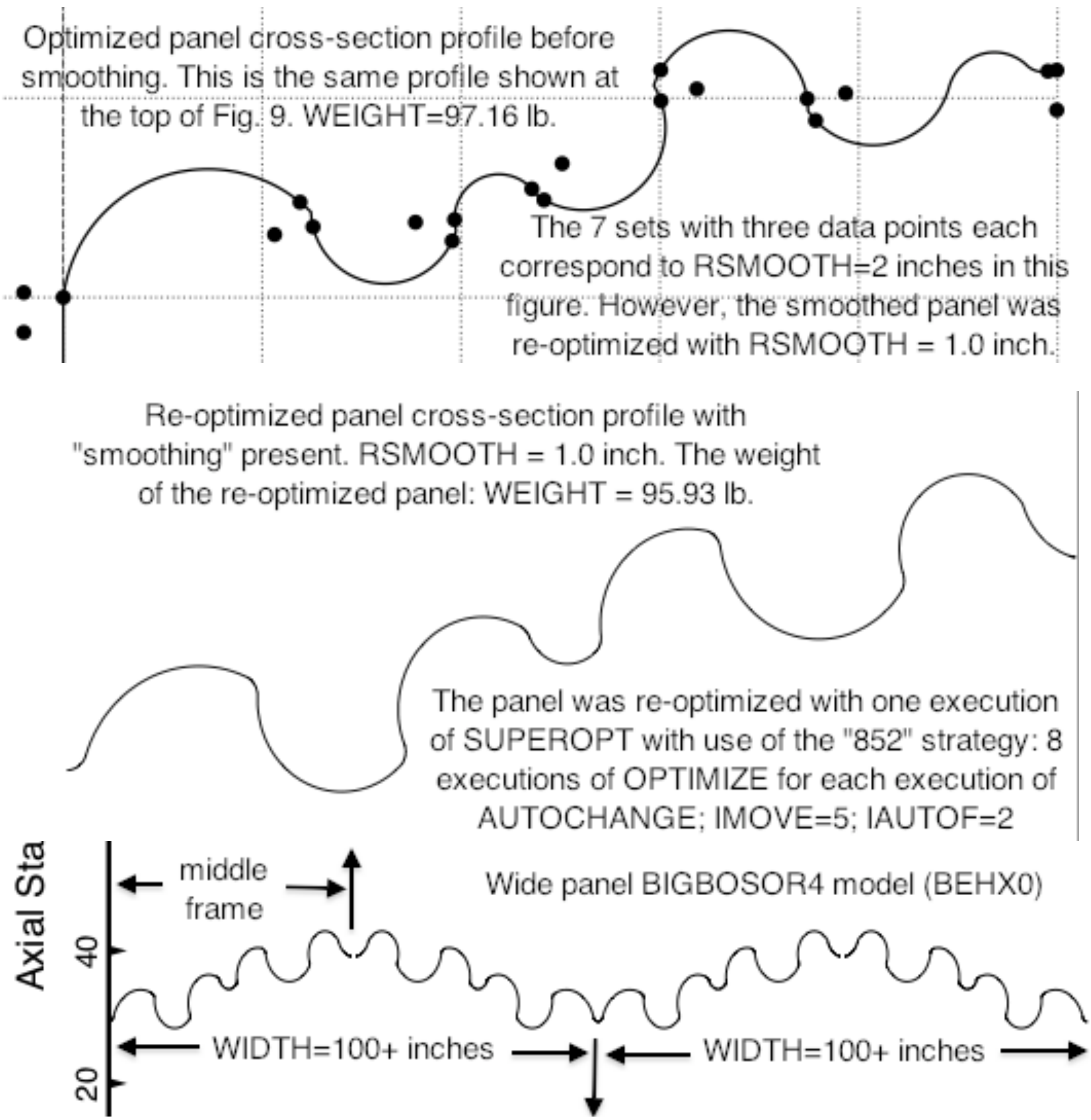


Fig. 31 **Optimization of the "smoothed" version** of the specific case called "fold98updown": **Top frame:** the starting design, which is the optimized design obtained before the introduction of "smoothing" cylindrical segments; **Middle frame:** the re-optimized design including "smoothing" segments with RSMOOTH = 1.0 inch; **Bottom frame:** the re-optimized "smoothed" panel cross-section profile extended to a wide panel of width, 2xWIDTH = 200 inches. The wide panel input file for BIGBOSOR4 is called "fold98updown.BEHX0".

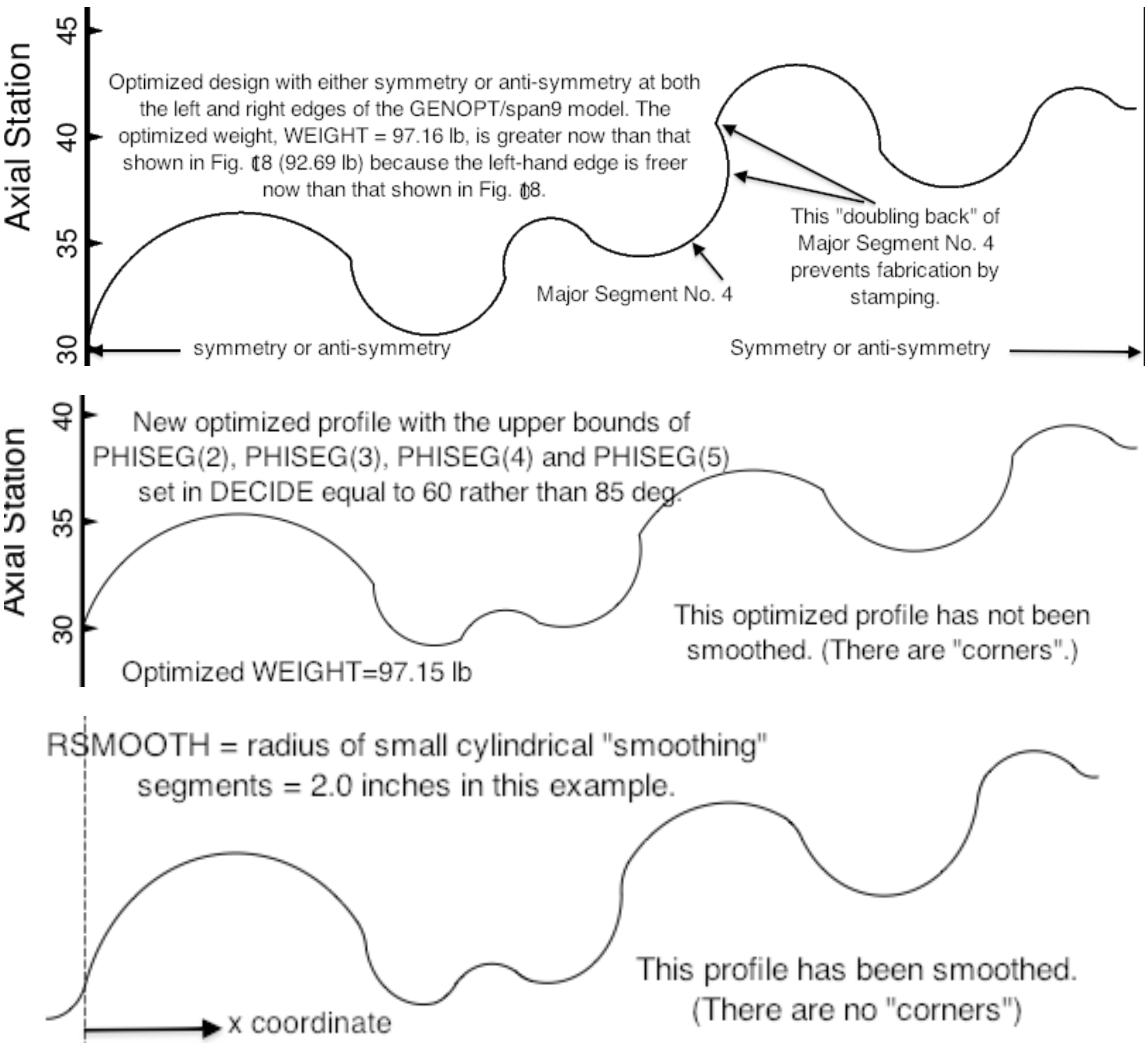


Fig. 32 **Two optimum designs** of the special case called “**fold98updown**” with “symmetry-antisymmetry” (“**NEW**”) boundary conditions applied along both the left-hand and right-hand longitudinal edges:
Top: The same optimized profile shown at the top of Fig. 9 (not smoothed; “corners” are present.)
Middle: The panel is re-optimized with use of the Fig. 9 design as a starting design. (“Corners” are present.)
Bottom: This profile is the same as that shown in the middle frame except that the “corners” have been smoothed and the left and right ends have zero slope in the x-direction. There has been no further optimization. The purpose of lowering the upper bounds of PHISEG(2), PHISEG(3), PHISEG(4) and PHISEG(5) is to try to come up with an optimum design which can be fabricated by stamping, that is, an optimum design with no “doubling back” such as that exhibited near the right-hand end of Major Segment No. 4 in the top frame.

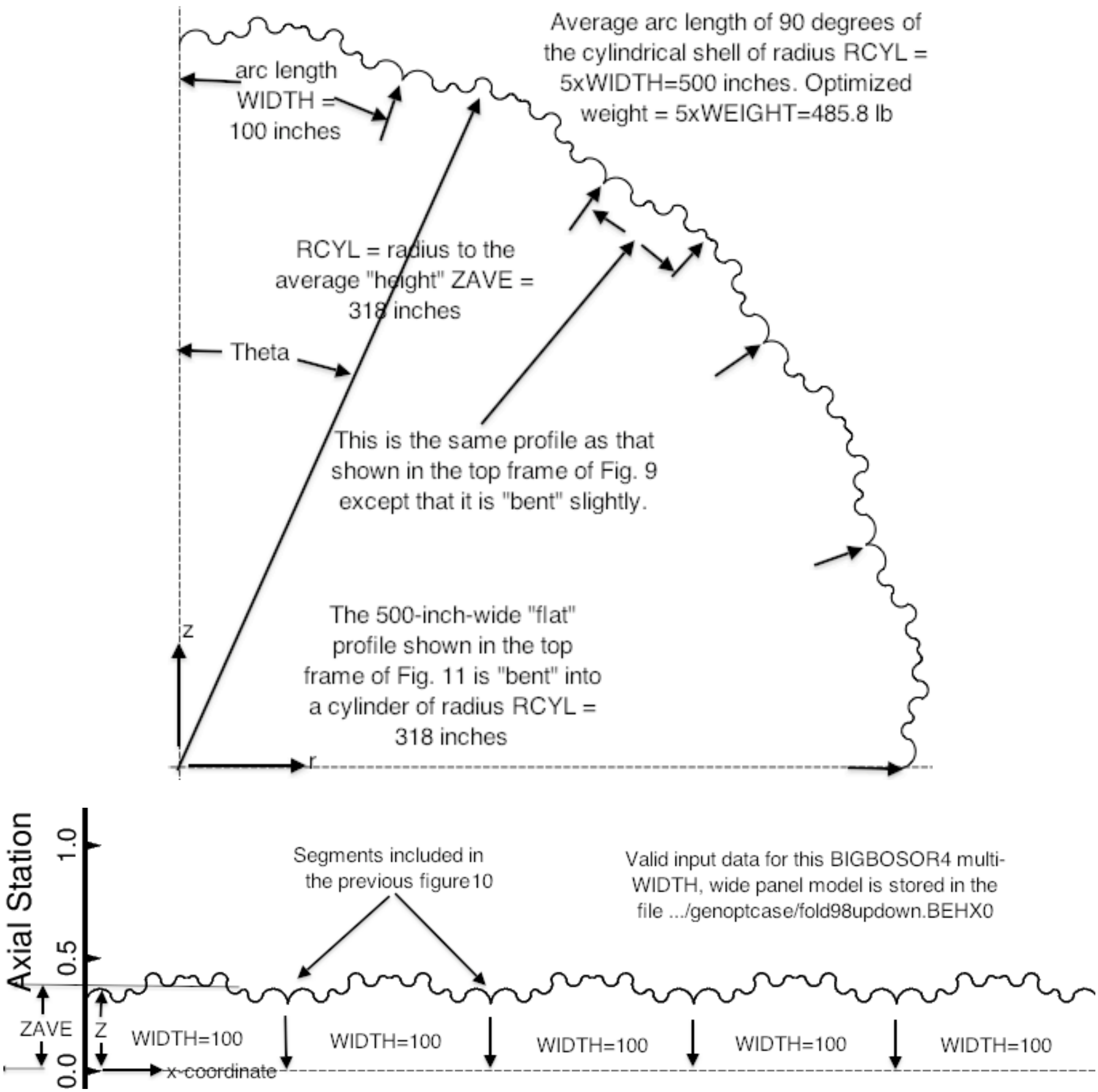
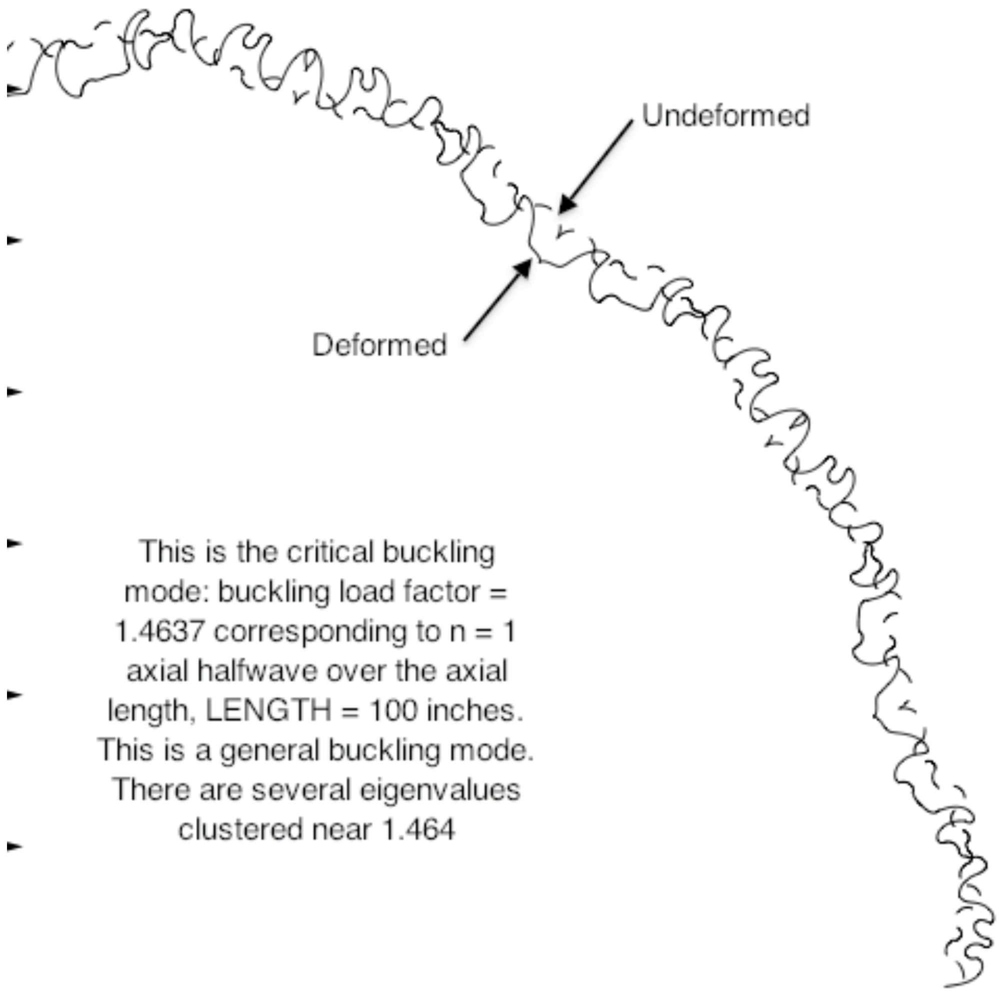


Fig. 33 Specific case called **"fold98updown"**: The BIGBOSOR4 multi-WIDTH flat wide panel model shown in the bottom frame here and in the top frame of Fig. 11 is **"bent" inextensionally into 90 degrees of a cylindrical shell with an average radius, RCYL = 318 inches**. The previously optimized weight of one section of width, WIDTH=100 inches, is 97.16 lb (top frame of Fig. 9). Therefore, the weight of 90 degrees of the cylindrical shell is 5 x 97.16 = 485.8 lb. The next figure shows buckling modes of this cylindrical shell.



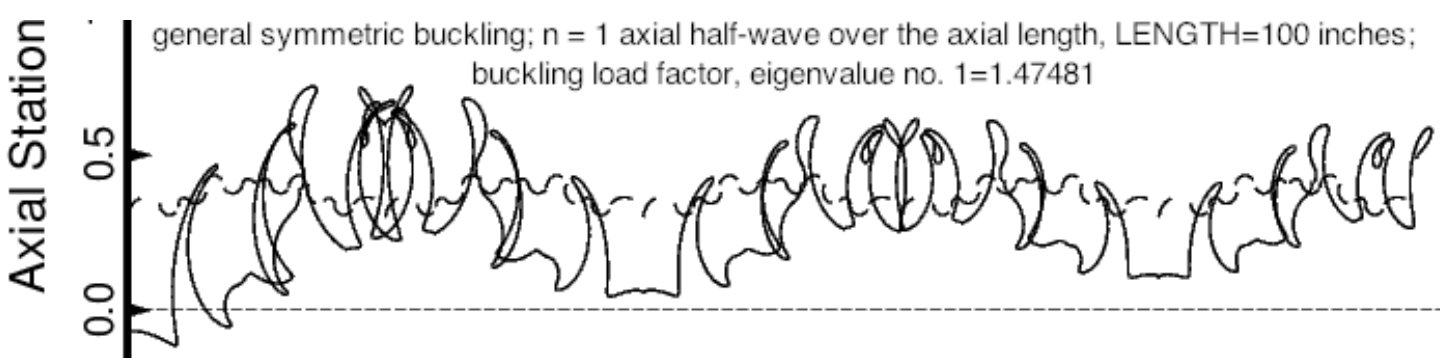


Fig. 34 Specific case called "fold98updown" mapped onto a cylindrical surface with radius, RCYL=318 inches. **Top:** The critical buckling mode of the 90-degree cylindrical shell shown in the previous figure corresponds to general buckling of the type shown in the second frame in Fig. 11 and reproduced as the bottom frame here. **Bottom:** General buckling of the "flat" multi-WIDTH (same as the second frame in Fig. 11). The buckling load factor of the "flat" panel, 1.47481, is close to that for the corrugated cylindrical shell: 1.4637.

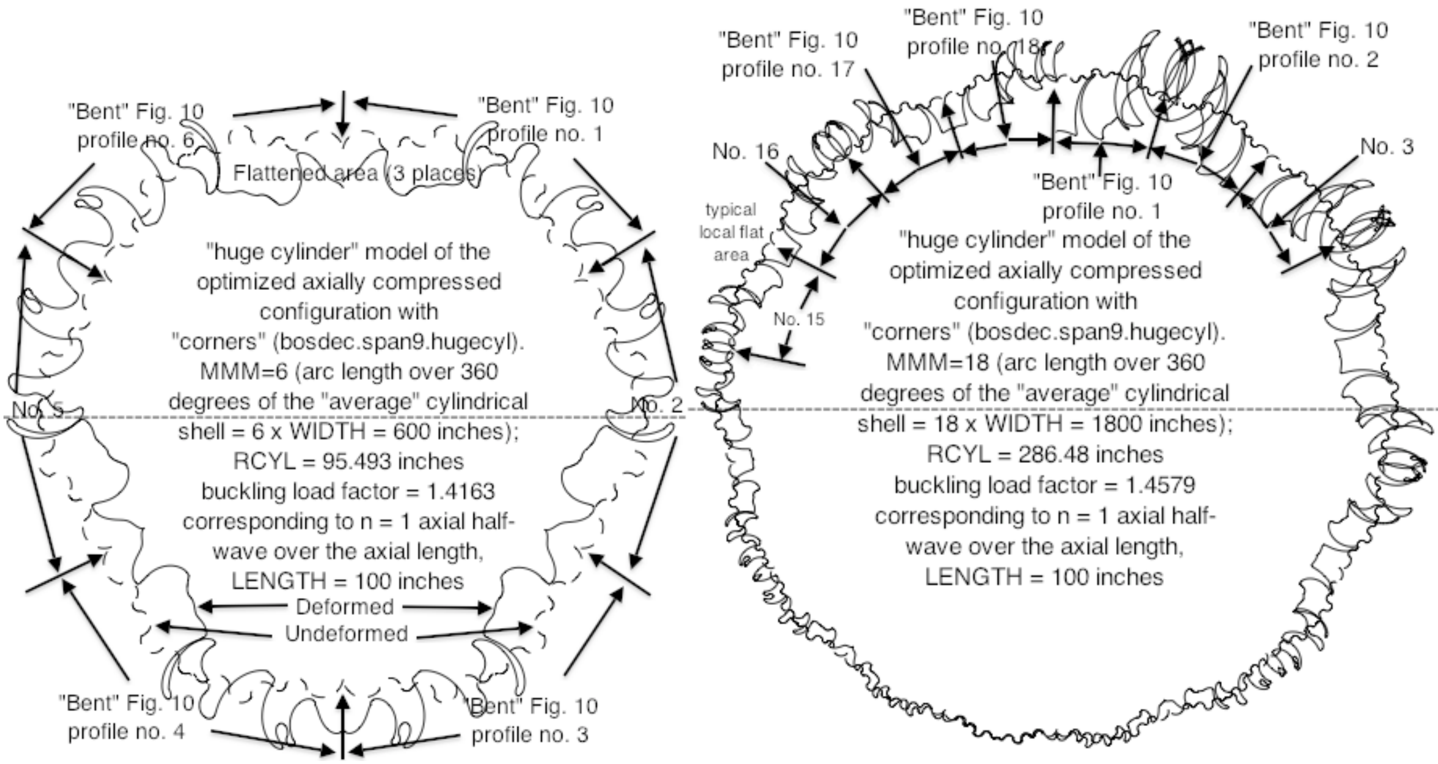


Fig. 35 **The optimized specific case with "corners" called "fold98updown" mapped onto a cylindrical surface with radius = RCYL**. The cross-section profile of arc length = WIDTH = 100 inches is the same as that shown for the undeformed cross sections plotted in Fig. 10. In this case the radii, RCYL, are established so that the "flat" (flat in the average sense) profile with arc length MMM x WIDTH maps into a complete (360 degree) cylindrical shell.

Left-hand side: MMM = 6 and RCYL = 95.493 inches. The 6 identical undeformed sectors labeled "'Bent' Fig. 10 profile no. i", i = 1, 2,…, 6 have the same profile as that of the undeformed structure shown in Fig. 10 except that this profile now follows the curved cylindrical surface. Because of the particular shape of the optimized undeformed profile shown in Fig. 10, adjacent halves of the six neighboring sectors form six flattened areas. The buckling load factor, 1.4163, is somewhat lower than that for the "flat" profile (lowest buckling load factor = 1.4741 printed in the top frame of Fig. 10) perhaps because the averaged cylindrical shell has these six average "flattened" areas that act as imperfections.

Right-hand side: MMM = 18 and RCYL = 286.48 inches. The buckling load factor, 1.4579, is much closer to that for the "flat" profile (1.4741) perhaps because the 18 "flattened" areas between adjacent halves of the 18 neighboring sectors around the circumference of the cylindrical shell are much less pronounced than the six flattened areas displayed in the left-hand plot, for which MMM = 6.

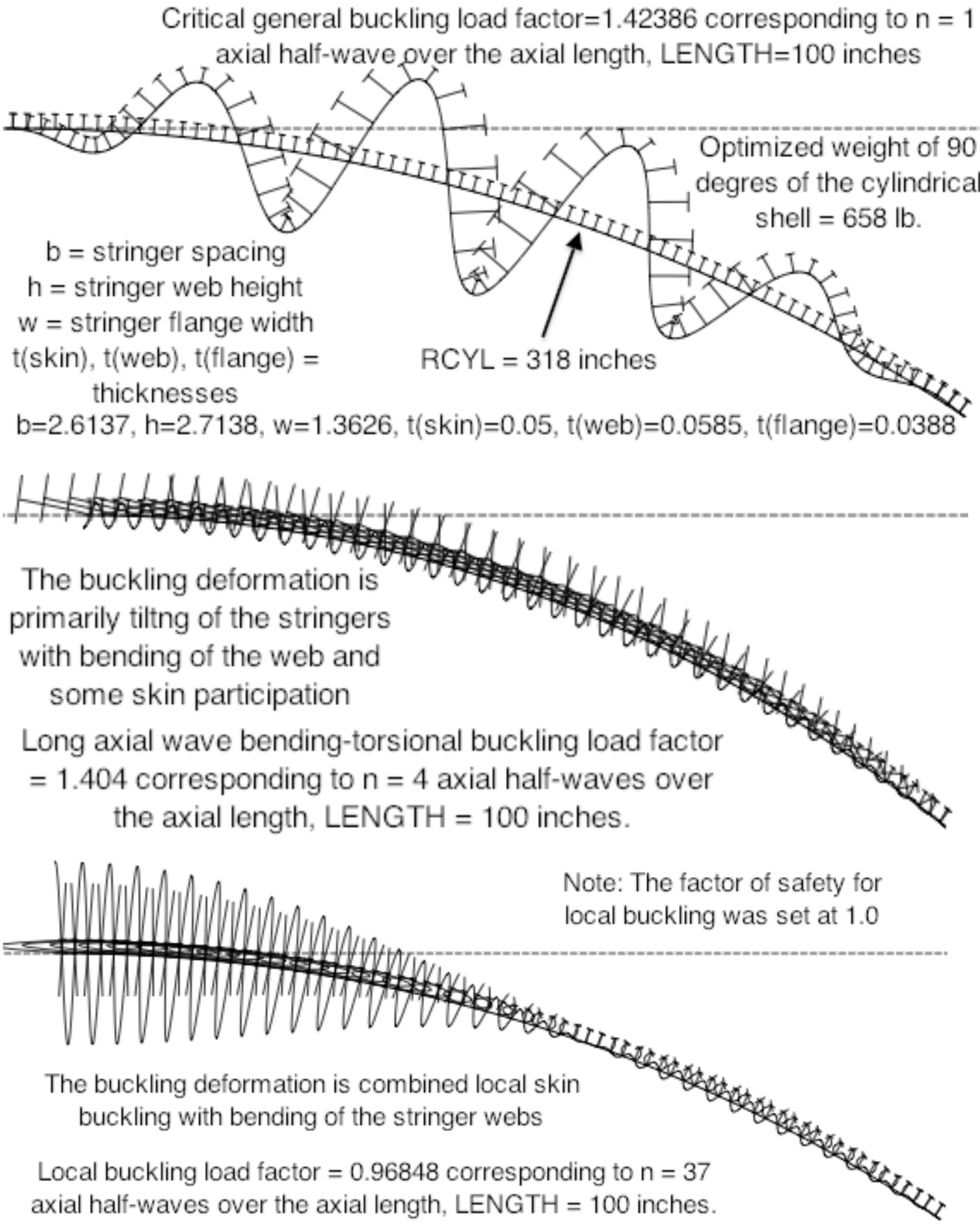


Fig. 36 **Three buckling modes of an axially compressed externally T-stringer-stiffened cylindrical shell**, "equivalent" (same radius and material) to that shown in Figs. 33 and 34, was optimized by PANDA2 [31]. The weight of 90 degrees of this optimized T-stiffened cylindrical shell is **658 lb**. (Compare with **485.8** lb for the optimized complex corrugated cylindrical panel shown in Figs. 33 and 34.)

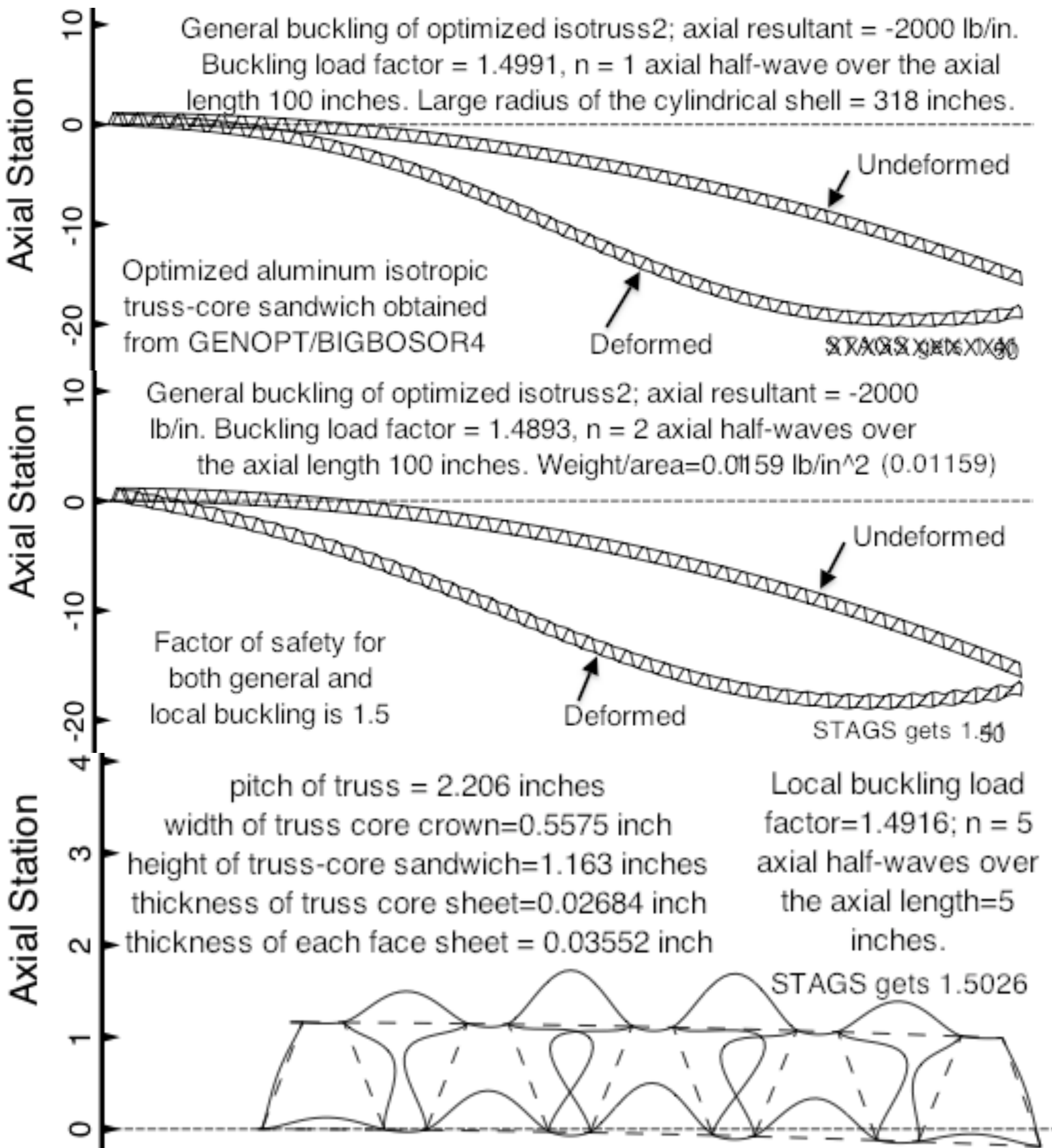


Fig. 37a BIGBOSOR4 models of **general and local buckling of an optimized aluminum cylindrical truss-core sandwich panel** under uniform axial compression, 2000 lb/in normal to the page. The panel was optimized by GENOPT/BIGBOSOR4/trusscomp [24]. The weight of 90 degrees of the optimized cylindrical shell is 579 lb compared to 485.8 lb for the optimized cylindrical shell with the complex corrugated cross-section profile. The STAGS prediction of the critical general buckling mode shape and load factor (1.5022) is given in Fig. 37b. The results from a much larger HUGEBOSOR4 model are shown in Fig. A19 (Appendix 6).

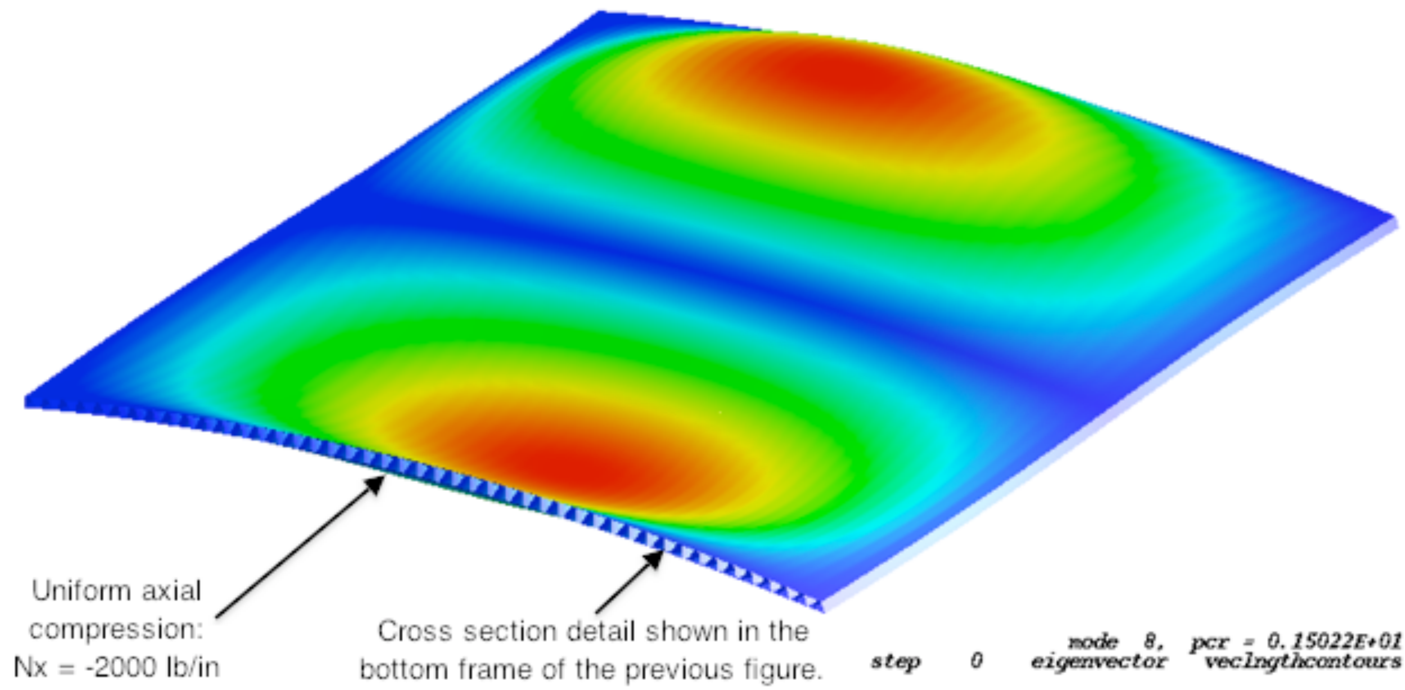


Fig. 37b **The same optimized truss-core sandwich cylindrical panel** as that shown in the top two frames of the previous figure. Shown here are STAGS predictions of the critical general buckling mode and its associated buckling load factor, 1.5022. The STAGS prediction of general buckling agrees very well with that for the same optimized cylindrical shell obtained from the GENOPT/trusscomp/BIGBOSOR4 model shown in the middle frame of Fig. 37a (Critical buckling load factor from BIGBOSOR4 = 1.4893, n(critical) = 2 axial half-waves).

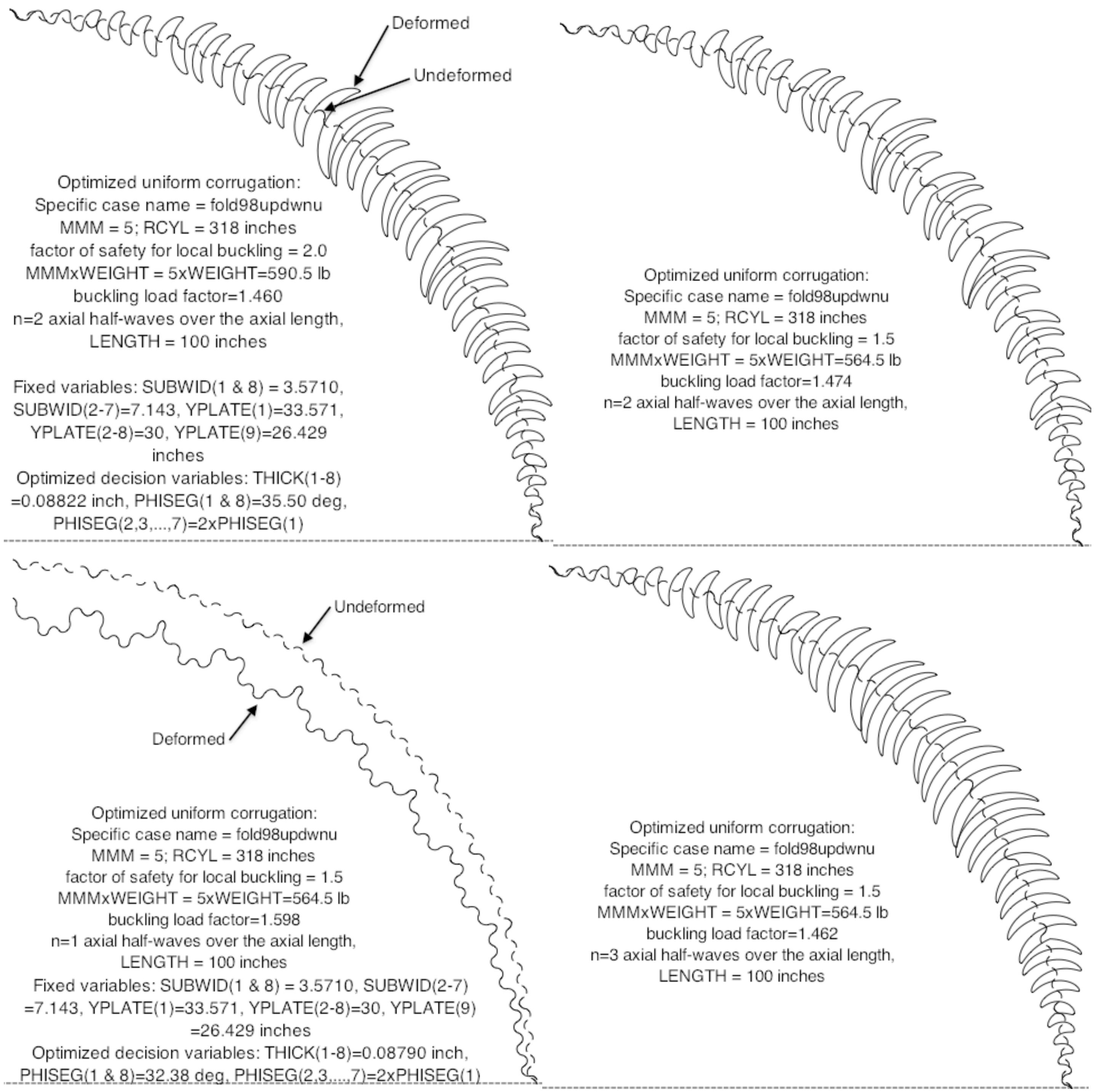


Fig. 38 The specific case called **"fold98updwnu"**: Optimized panel with **uniform corrugation**. The optimized undeformed cross-section profile in the upper left-hand corner is the same as that shown in the bottom frame of Fig. 18, except that this undeformed profile is mapped onto a cylindrical surface with radius = RCYL = 318 inches. The other three undeformed profiles are optimized profiles with the factor of safety for local buckling set equal to 1.5 instead of 2.0. Compare the weight, 564.5 lb, with that listed near the top of Fig. 33: 485.8 lb.

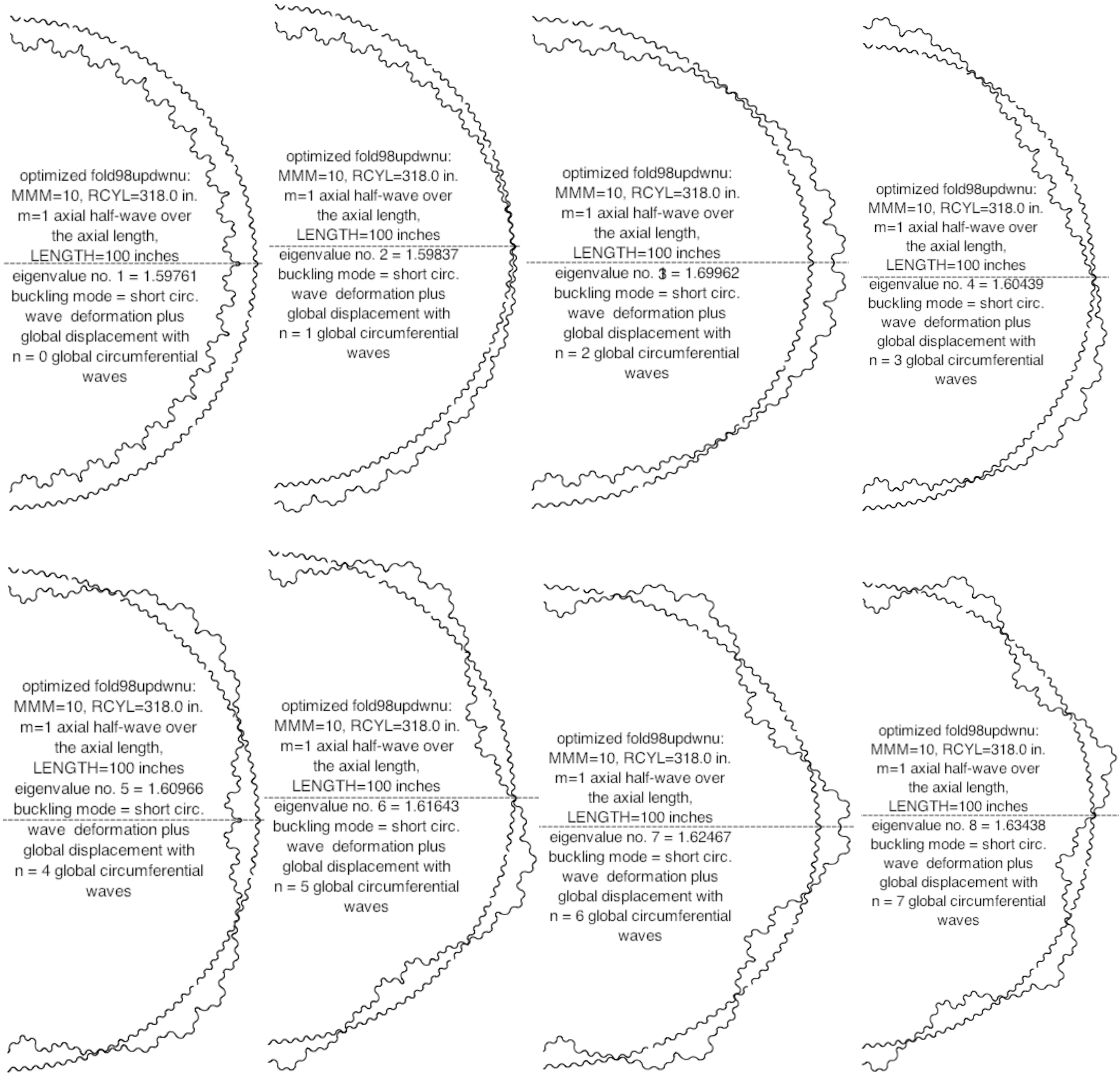


Fig. 39 The specific case called **"fold98updwnu"**: Optimized panel with **uniform corrugation**. The number of repeating segments, each of arc length = WIDTH = 100 inches, is 10, that is, MMM = 10, and the radius of the cylindrical shell, RCYL = 318 inches. 180 degrees of the cylindrical shell is included in the large BIGBOSOR4 model, which contains 160 segments. The second mode in the top row is the same as the mode in the lower left-hand corner of the previous figure. All these buckling modes have 1 axial half-wave over the length, LENGTH=100 inches. All the modes are combinations of short and long circumferential wavelengths, with fairly closely clustered eigenvalues.

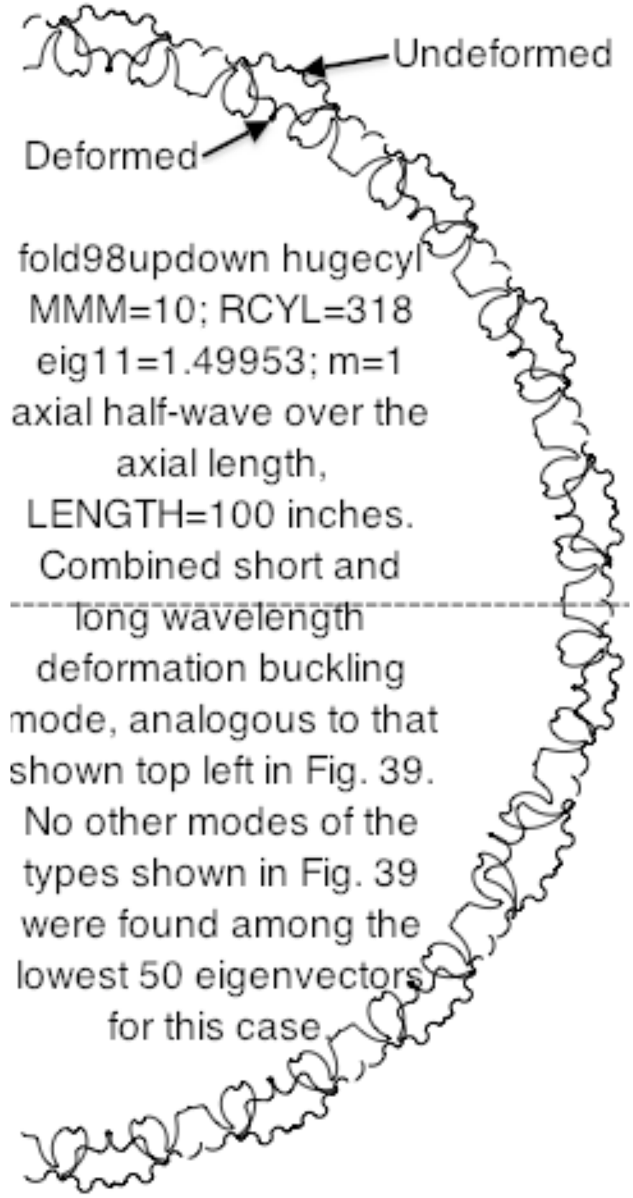


Fig. 40 The specific **complexly corrugated** case called **"fold98updown"**: This is the eigenvector corresponding to the 11th eigenvalue for the "huge cylinder" model of the optimized cross-section profile shown at the top of Fig. 11 and mapped onto a cylindrical shell as shown in Fig. 33 via SUBROUTINE BOSDEC2 (part of the file called bosdec.span9.hugecyl), except that in Figs. 11 and 33 the total arc length is MMM x WIDTH = 5 x WIDTH = 500 inches, whereas in this figure the total arc length is MMM x WIDTH = 10 x WIDTH = 1000 inches, generating 180 degrees of the cylindrical shell with average radius, RCYL = 318 inches. The buckling mode shown here is analogous to that corresponding to the first (lowest) eigenvalue in the huge cylinder model of the optimized uniform corrugation shown in the top left frame of Fig. 39 (the specific case called "fold98updwnu"). No other "combined" short and long wavelength buckling modes of the type displayed in Fig. 39 were found among the 50 eigenvectors corresponding to the lowest 50 eigenvalues for this "fold98updown" case.

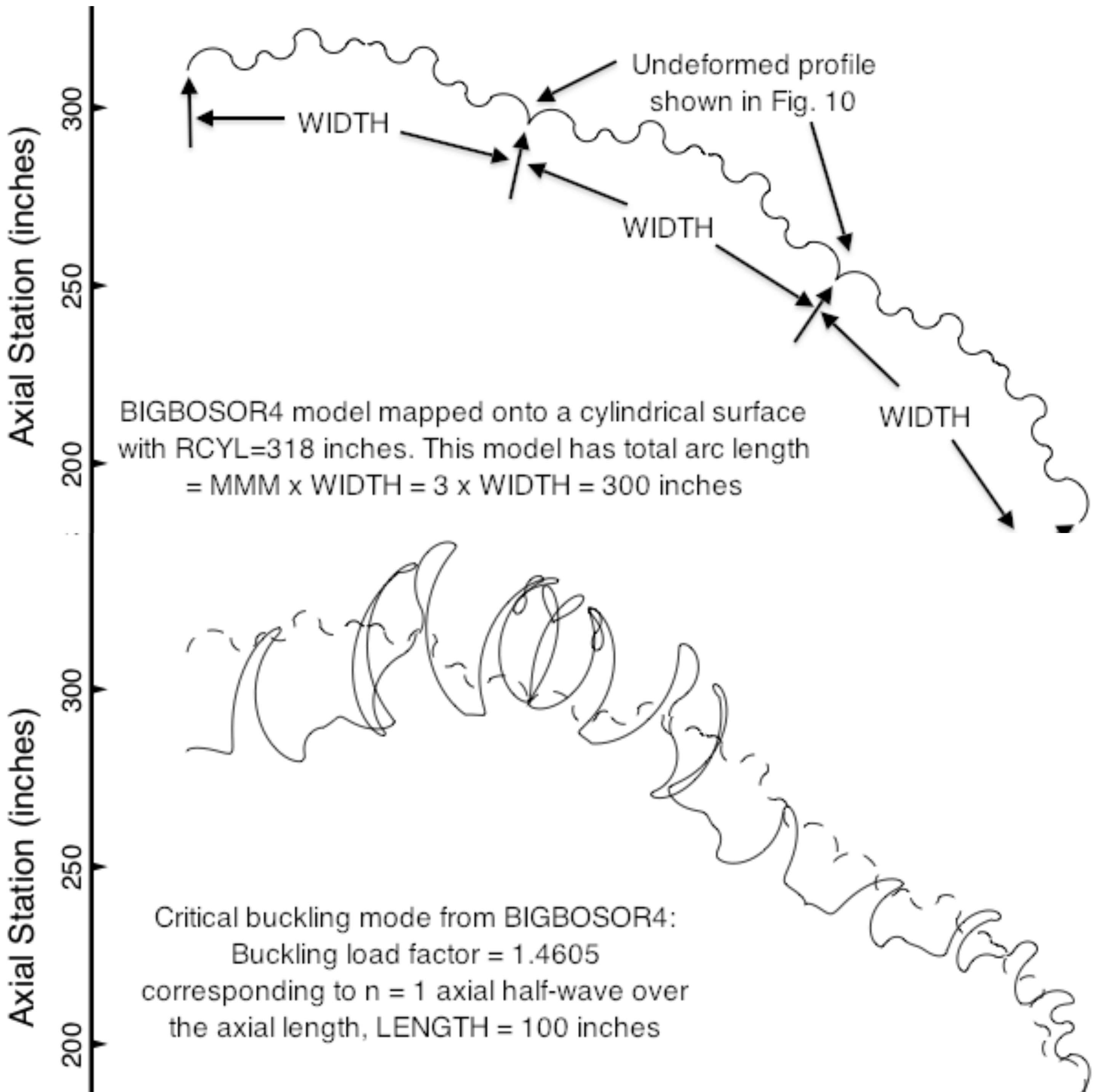
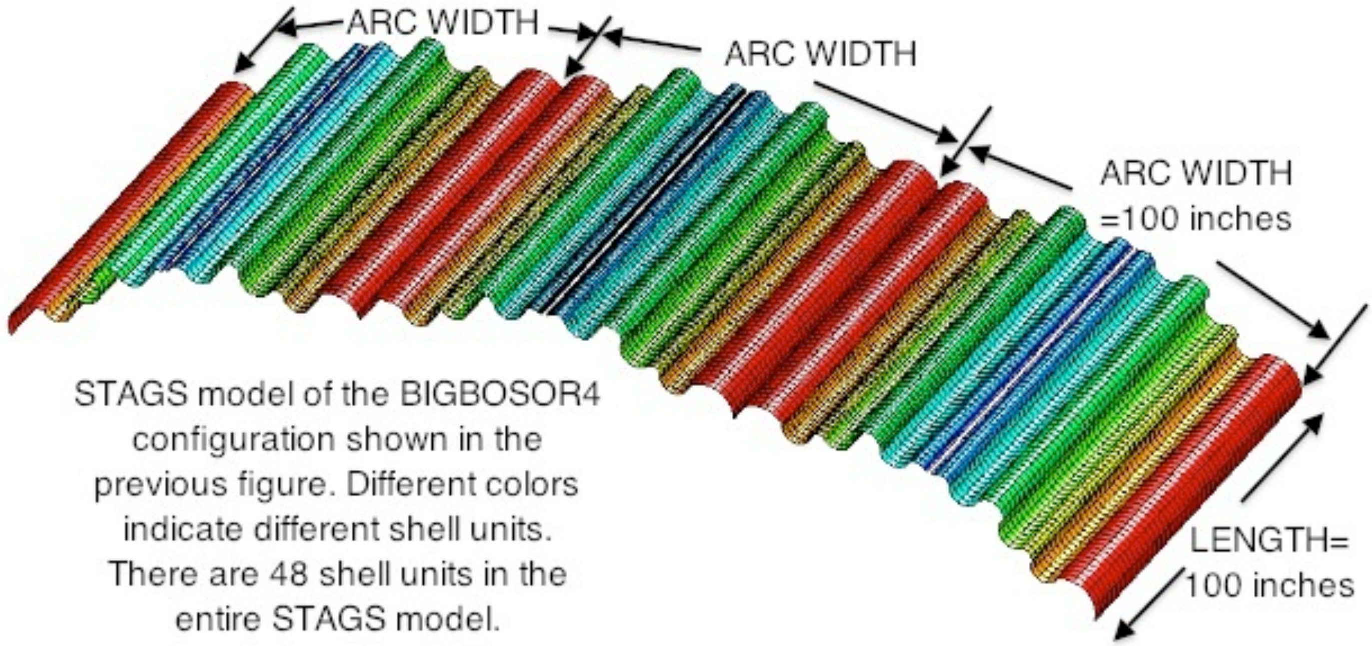


Fig. 41 Specific **complexly corrugated** case called **"fold98updown"**: The optimized complexly corrugated "flat" wide panel of width = 3xWIDTH is mapped onto a cylindrical surface with average radius, RCYL = 318 inches. **Top frame:** the undeformed profile. **Bottom Frame:** the critical buckling mode predicted by BIGBOSOR4. A STAGS model and the corresponding critical buckling mode predicted by STAGS are displayed in the next figure.



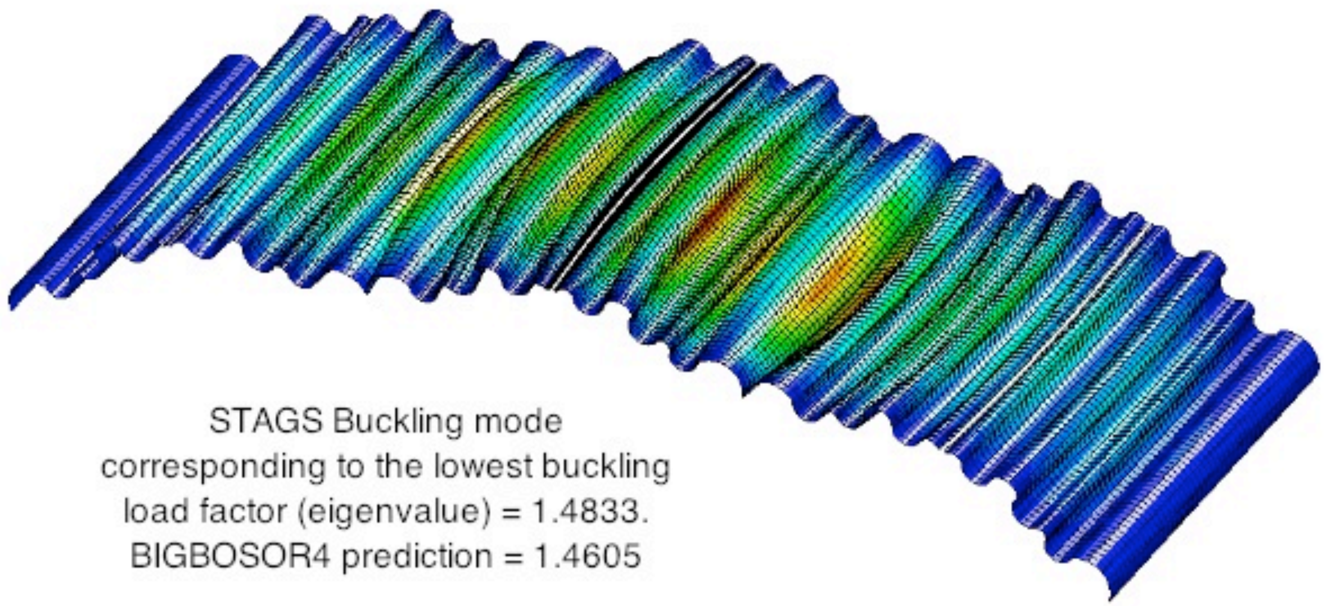


Fig. 42 **STAGS model (top) and buckling mode (bottom)** for the same optimized configuration analyzed by BIGBOSOR4 and shown in the previous figure. The specific case is called **"fold98updown"**.

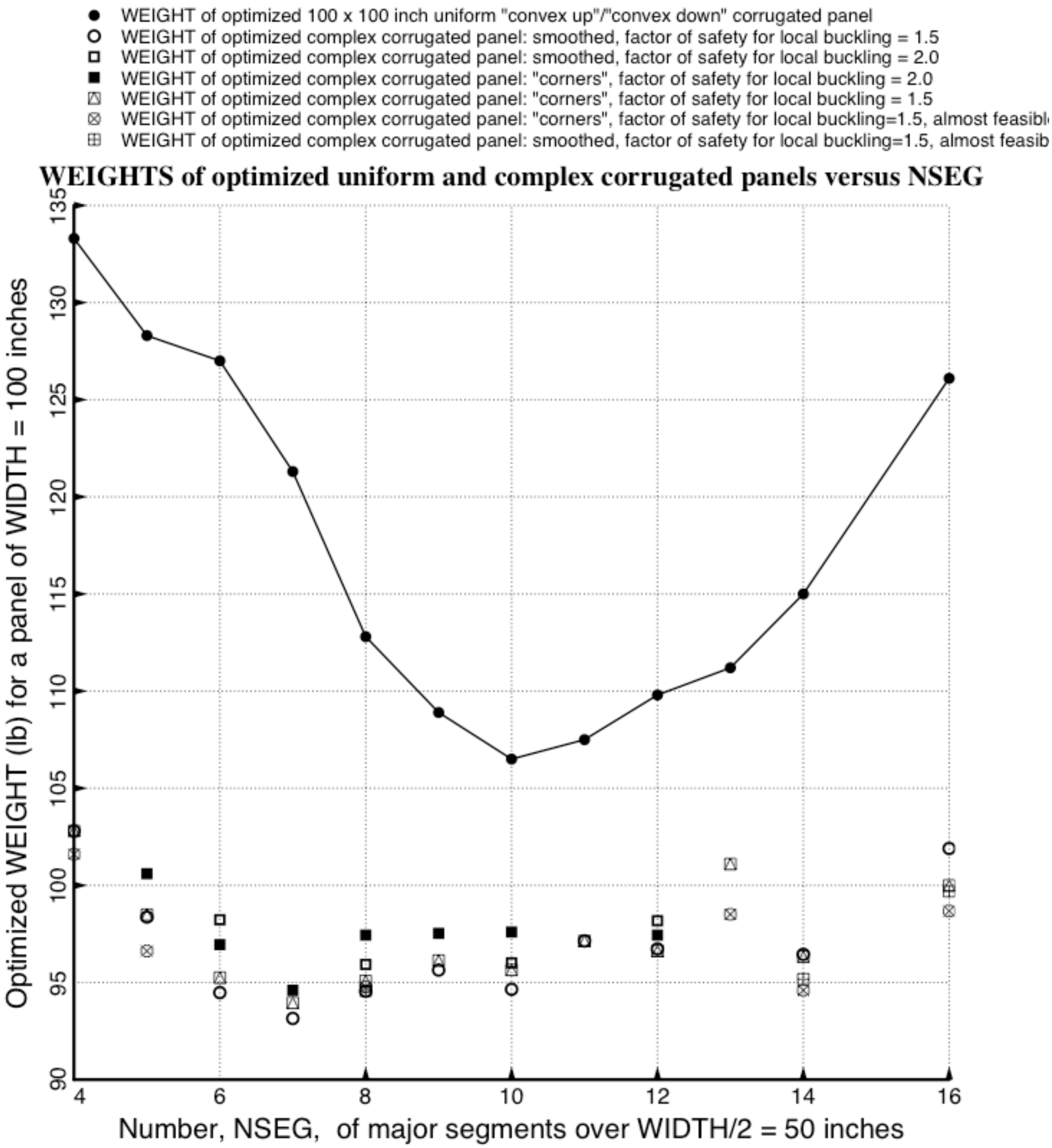
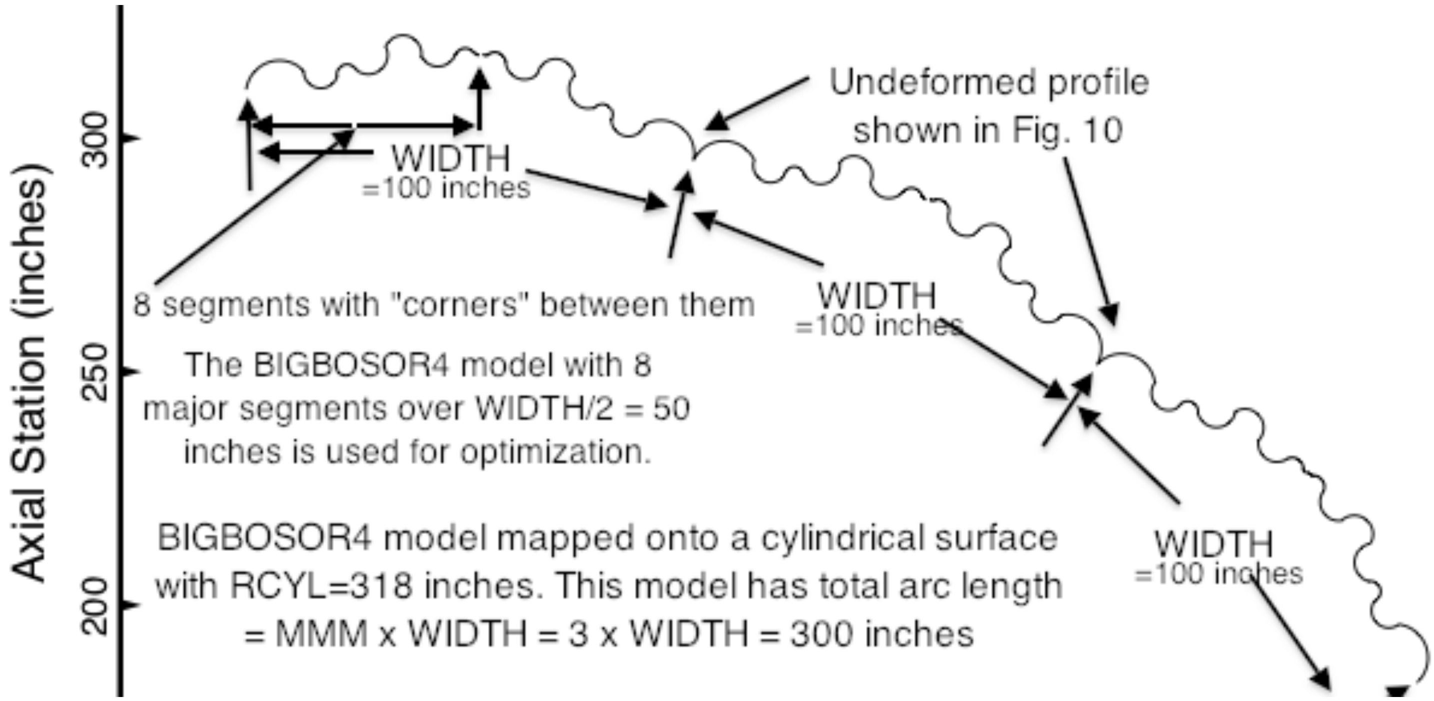


Fig. 43 **Optimized weights versus the number of major segments** (NSEG) spanning WIDTH/2 = 50 inches for **uniformly and complexly corrugated panels** with alternating “convex up” and “convex down” configurations. The uniformly corrugated panels (curve) are significantly heavier than the complexly corrugated panels. The minimum optimized weight for a complexly corrugated panel, 93.15 lb at NSEG = 7, is about 13 per cent lower than the minimum optimized weight for uniformly corrugated panels: 106.5 lb at NSEG = 10. Indications (described in Appendix 5) are that the optimized designs corresponding to NSEG = 13 and NSEG = 16 are not global optimum designs. See Fig. A18 and the relevant text in Appendix 5 for an explanation.



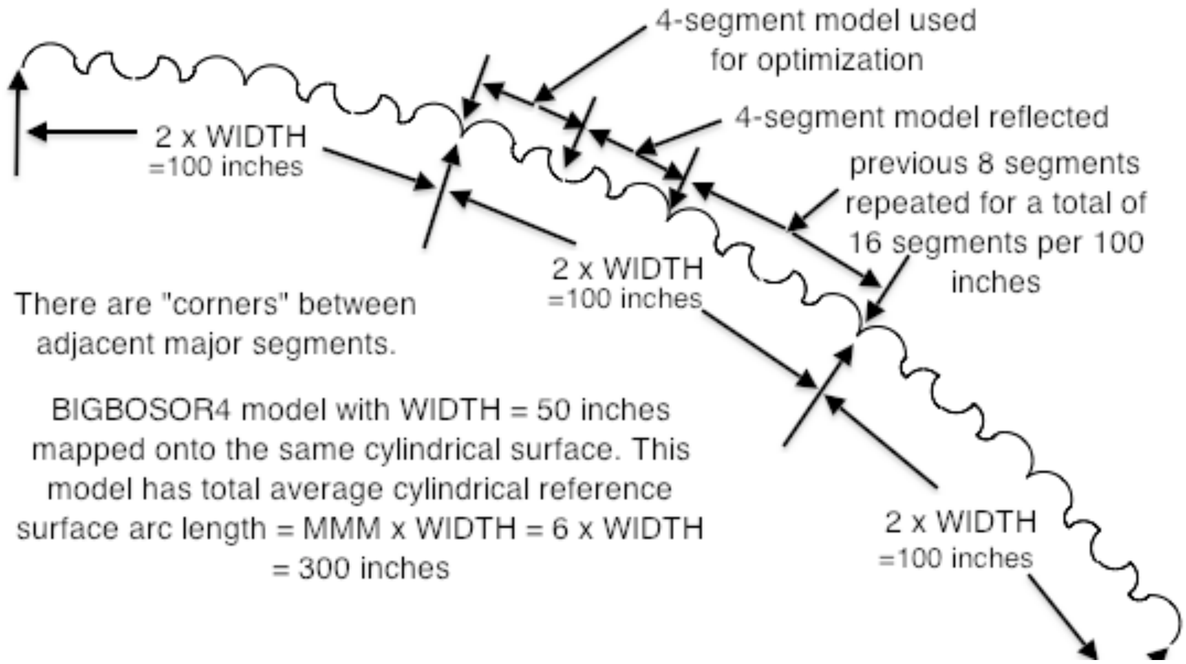


Fig. 44 Two optimized complex corrugated profiles **with "corners"**, extended and mapped onto the same cylindrical surface a surface with average radius, RCYL = 318 inches: **Top frame:** This is the same profile as that shown in the top frame of Fig. 41. WIDTH = 100 inches. The optimized half-width profile (first 8 segments indicated in this frame) is the same as that shown in the top frame of Fig. 9. The specific case name is **fold98updown**. **Bottom frame:** Optimized profile determined from a model in which WIDTH = 50 inches and in which there are 4 major segments over WIDTH/2 = 25 inches. The specific case name is **narw94updown**.

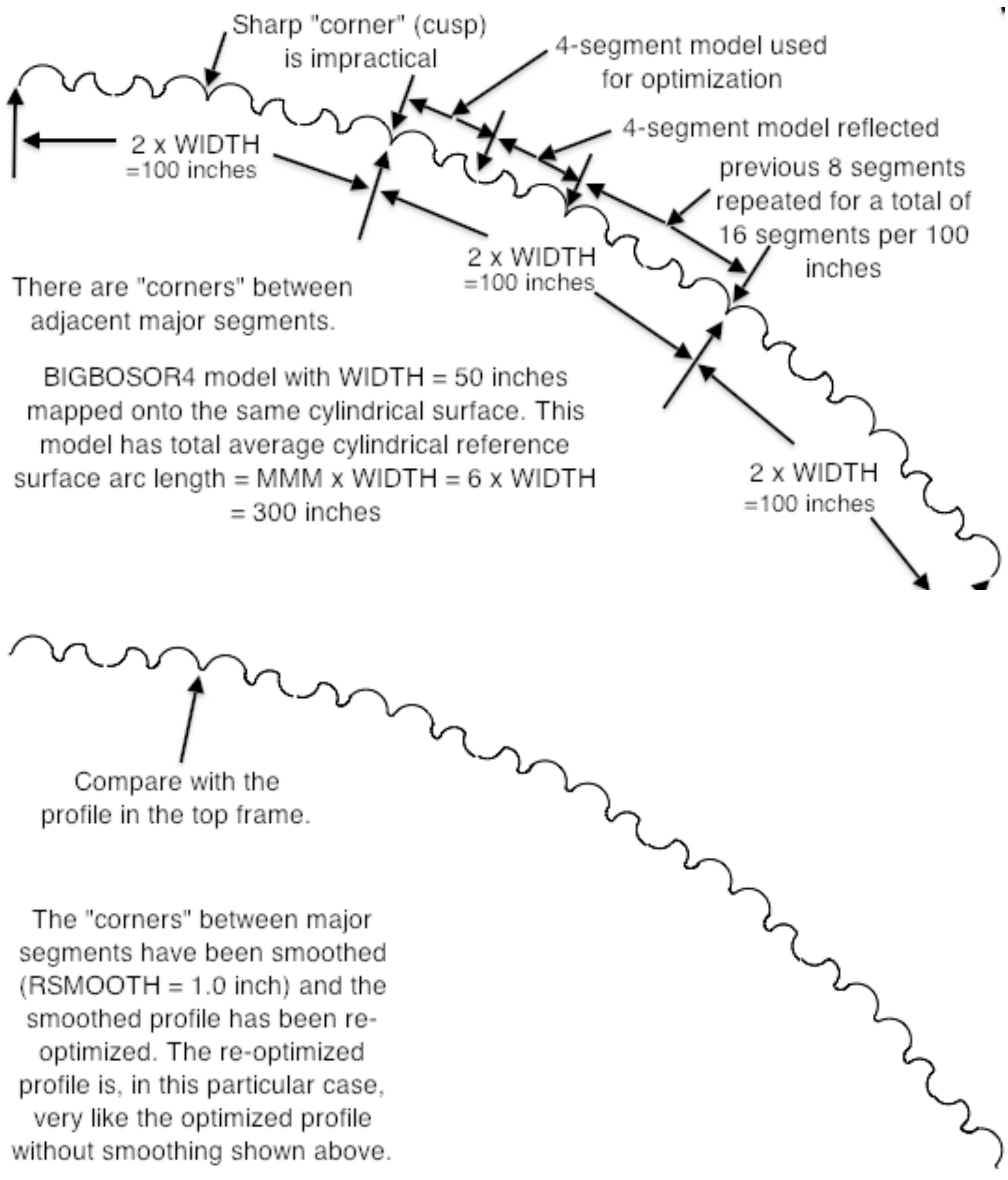


Fig. 45 **Top frame:** Same optimized extended and mapped profile as that shown in the bottom frame of the previous figure. **Bottom frame:** Re-optimized profile with smoothing present. RSMOOTH = 1.0 inch.

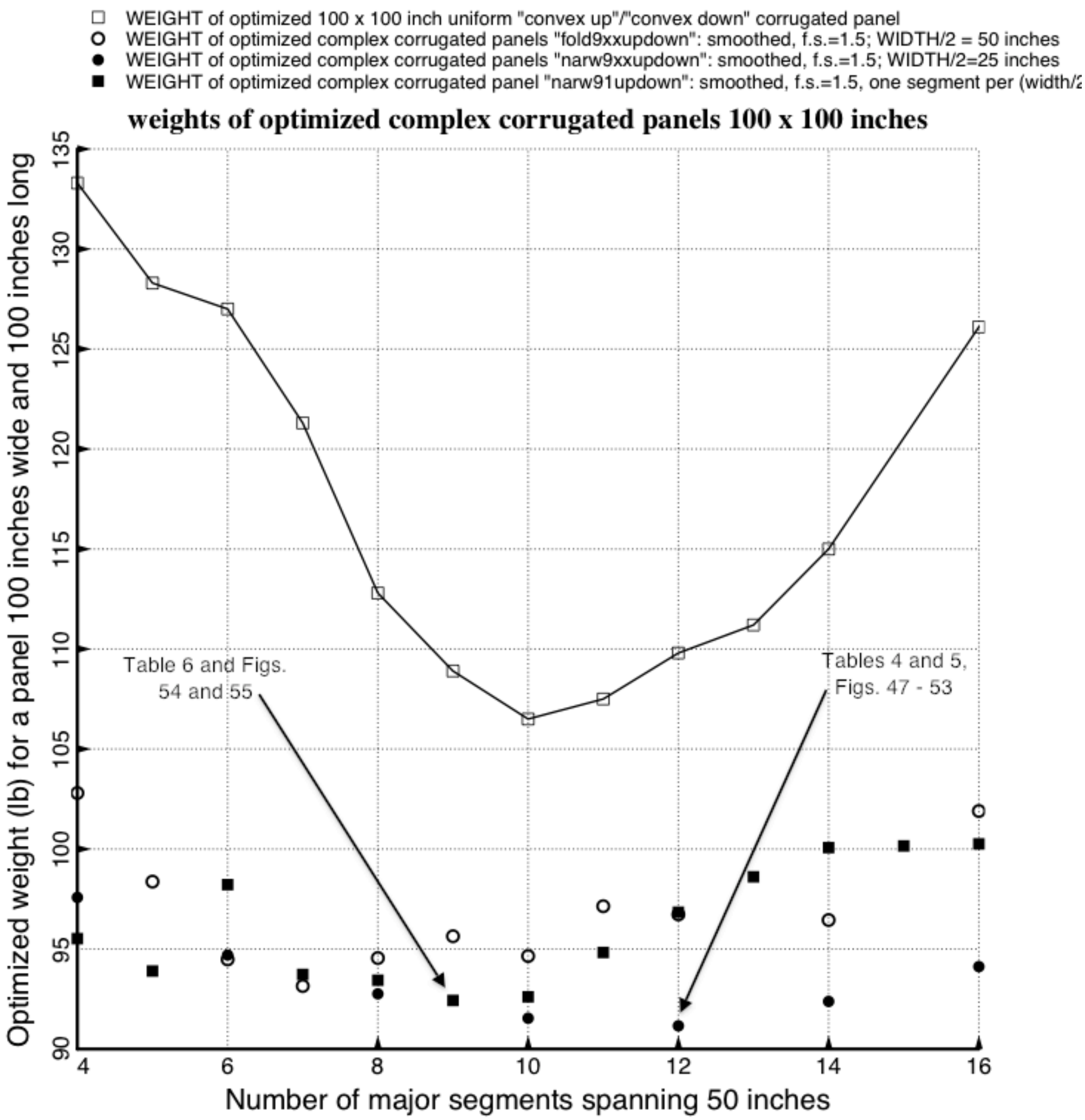


Fig. 46 **New optimized weights of 100 x 100 –inch panels (solid data points) in which panels that are narrower than WIDTH = 100 inches are used for optimization.** The curve for uniform corrugated panels and the open data points for complex corrugated panels are the same as those given in Fig. 43. The **solid data points** are lower than the open data points probably because there are many fewer decision variables needed for optimization of the narrower panels than are required for optimization of the panels with WIDTH = 100 inches. All of the **solid square data points** are generated from optimization models with only one major segment over half the panel width, therefore with the use of very few decision variables. See Table 6 and Fig. 49 for more information corresponding to the solid square data point plotted at the minimum weight: that data point plotted at "Number of major segments spanning 50 inches " = 9. It is surprising that this minimum weight (92.43 lb) is not far above the minimum weight (91.16 lb at 12 major segments) for the **solid round data points.** See Table 5 & Fig. 47 for more information corresponding to the solid round data point plotted at the minimum weight: that solid round data point plotted at "Number of major segments spanning 50 inches" = 12.

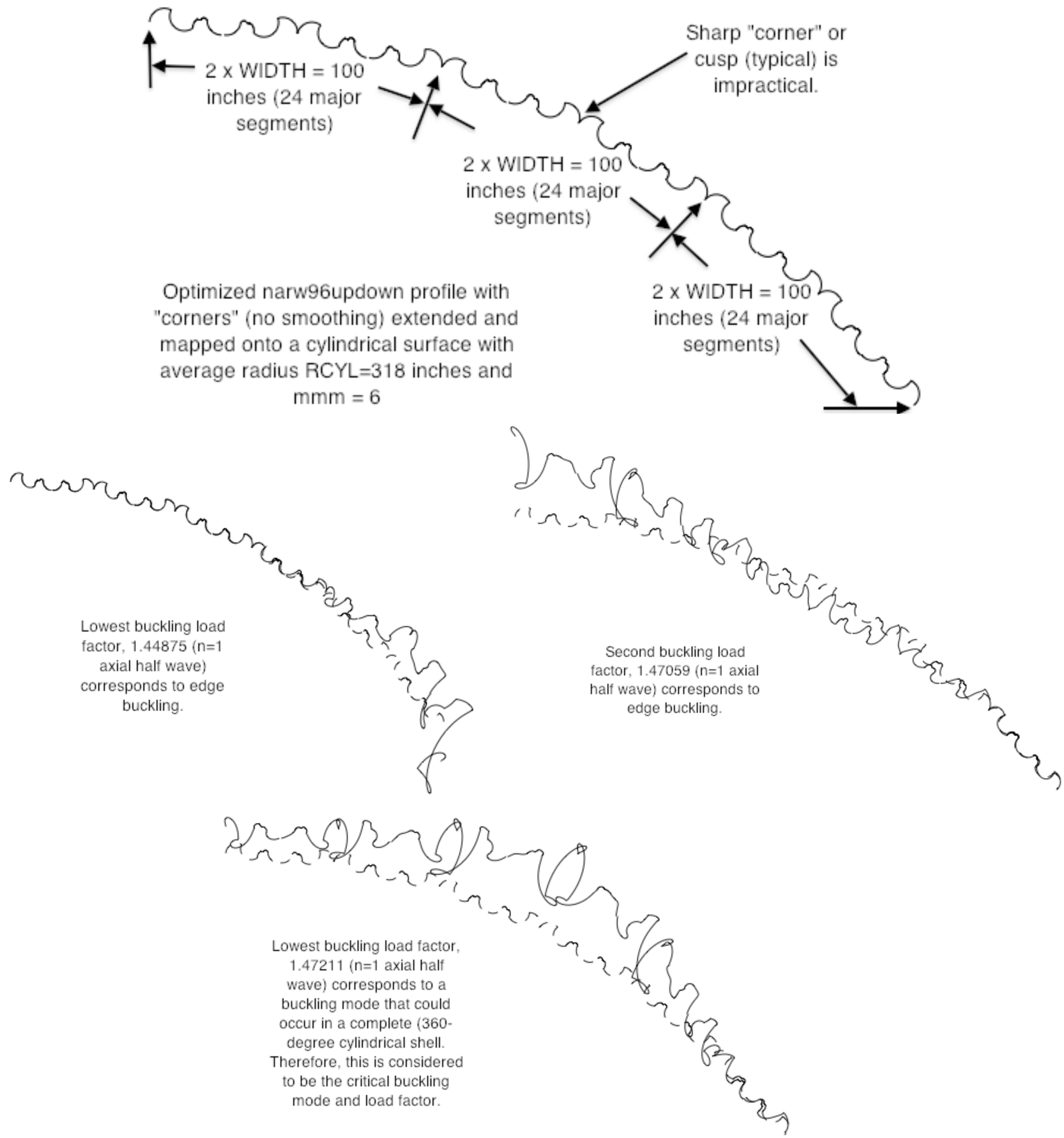


Fig. 47 **Top frame**: Optimized **narw96updown** profile with “corners” (no smoothing), extended and mapped onto a cylindrical surface, **Middle two frames**: The first two eigenvalues (buckling load factors) correspond to buckling in the neighborhoods of the edges; **Bottom frame**: The third eigenvalue, 1.47211, is the critical “realistic” buckling mode and load factor, that is, a buckling mode that could exist in a 360-degree cylinder.

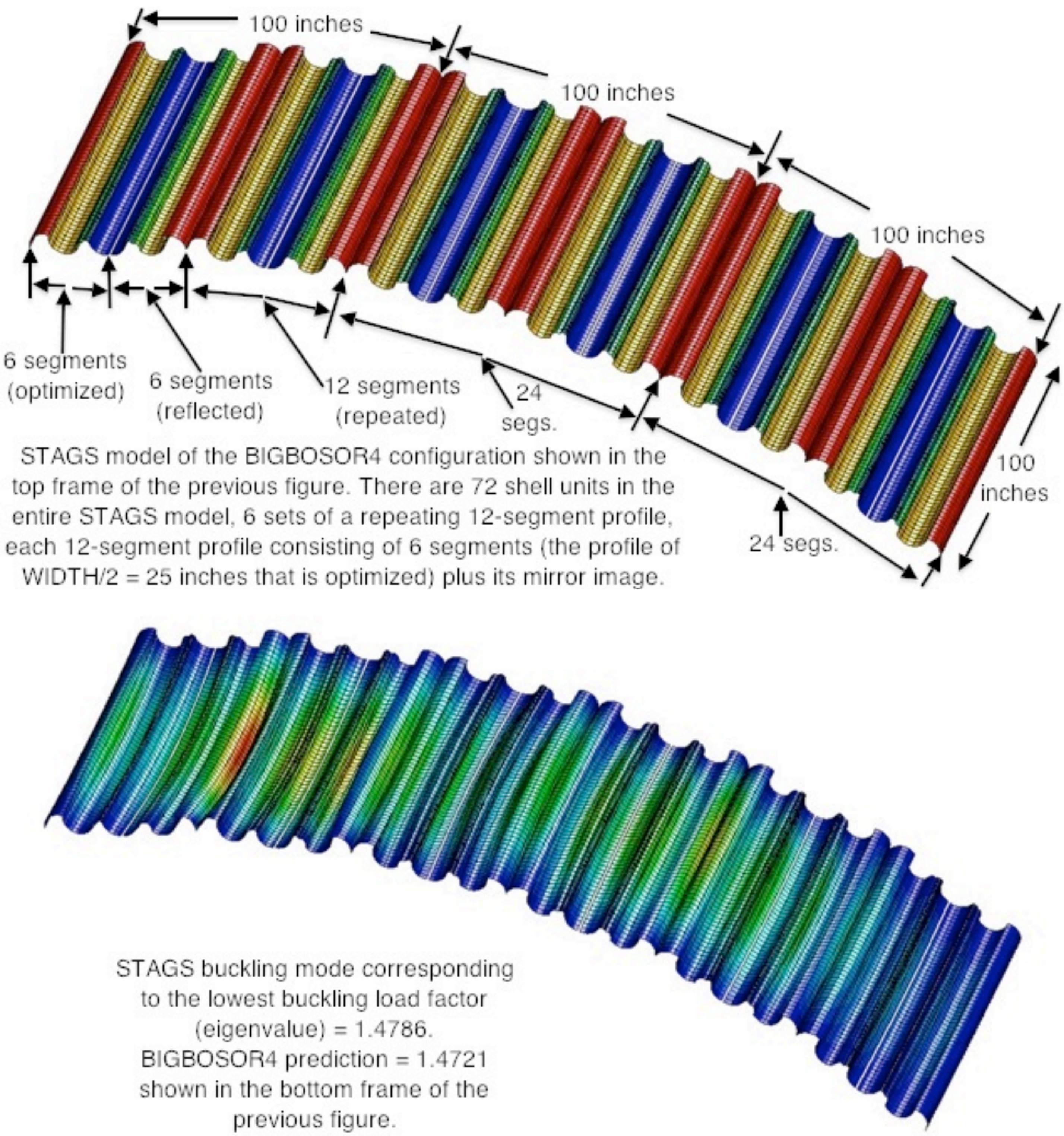


Fig. 48 **STAGS model (top) and buckling mode (bottom)** for the same optimized configuration analyzed by BIGBOSOR4 and shown in the previous figure. The specific case is called **"narw96updown" (with corners)**.

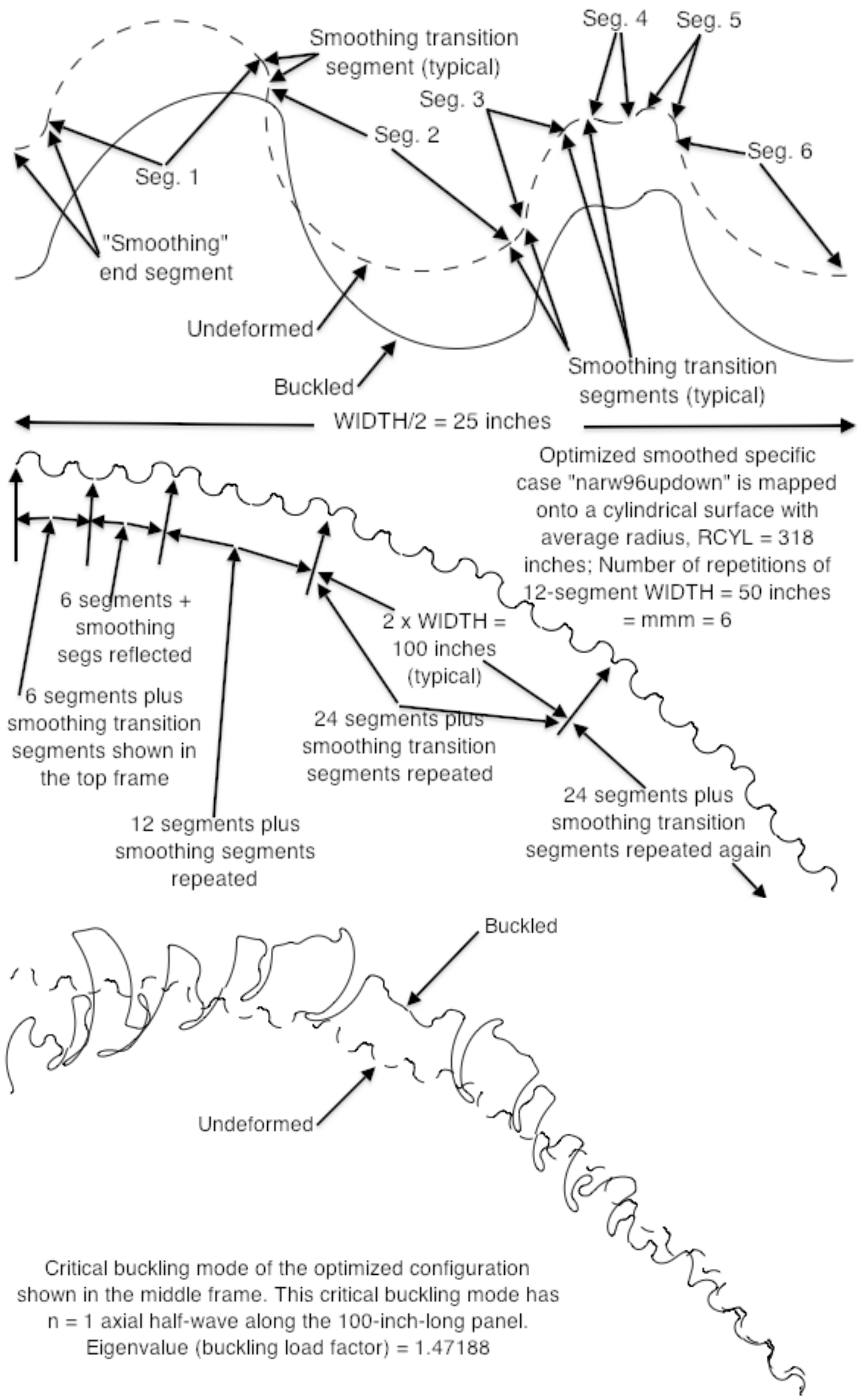


Fig. 49 Results for the specific case called "**narw96updown**", which has the optimized smoothed cross-section profile associated with the smallest weight (91.16 lb, Table 5) plotted in the Fig. 46. **Top frame:** Optimized profile and symmetric general buckling mode (buckling load factor = 1.4955, n = 1 axial half-wave over LENGTH=100 inches). **Middle frame:** Optimized profile expanded and mapped onto a cylindrical surface. **Bottom frame:** Critical buckling mode and load factor (1.47188) of the expanded and mapped profile.

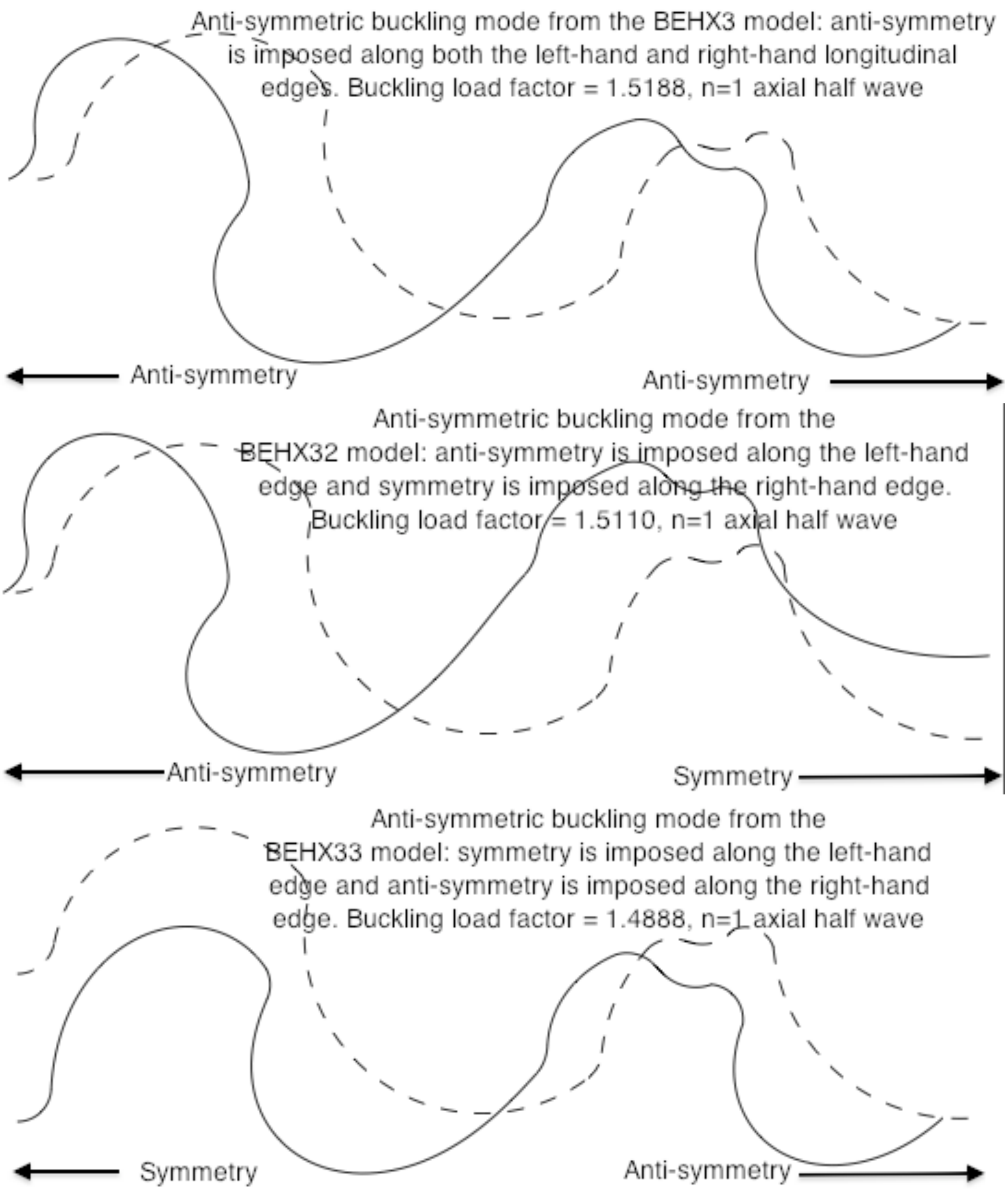


Fig. 50 Three **anti-symmetric buckling modes** of the optimized, smoothed specific case "**narw96updown**". These three buckling modes and load factors are computed in SUBROUTINE BEHX3. The lowest buckling load factor (in this case 1.4888) is used for determination of the design margin containing the name BUCASY (Table 5).

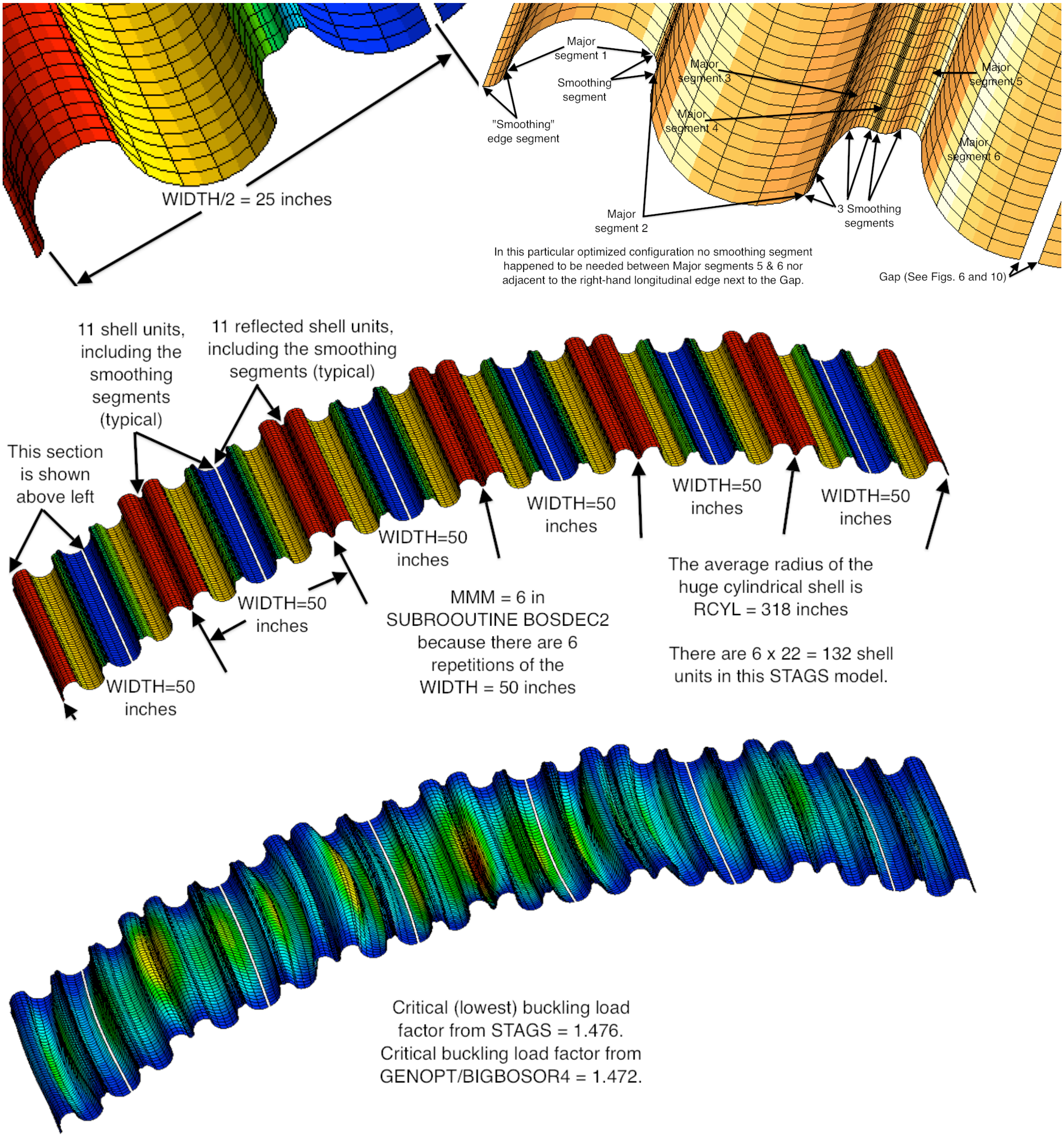
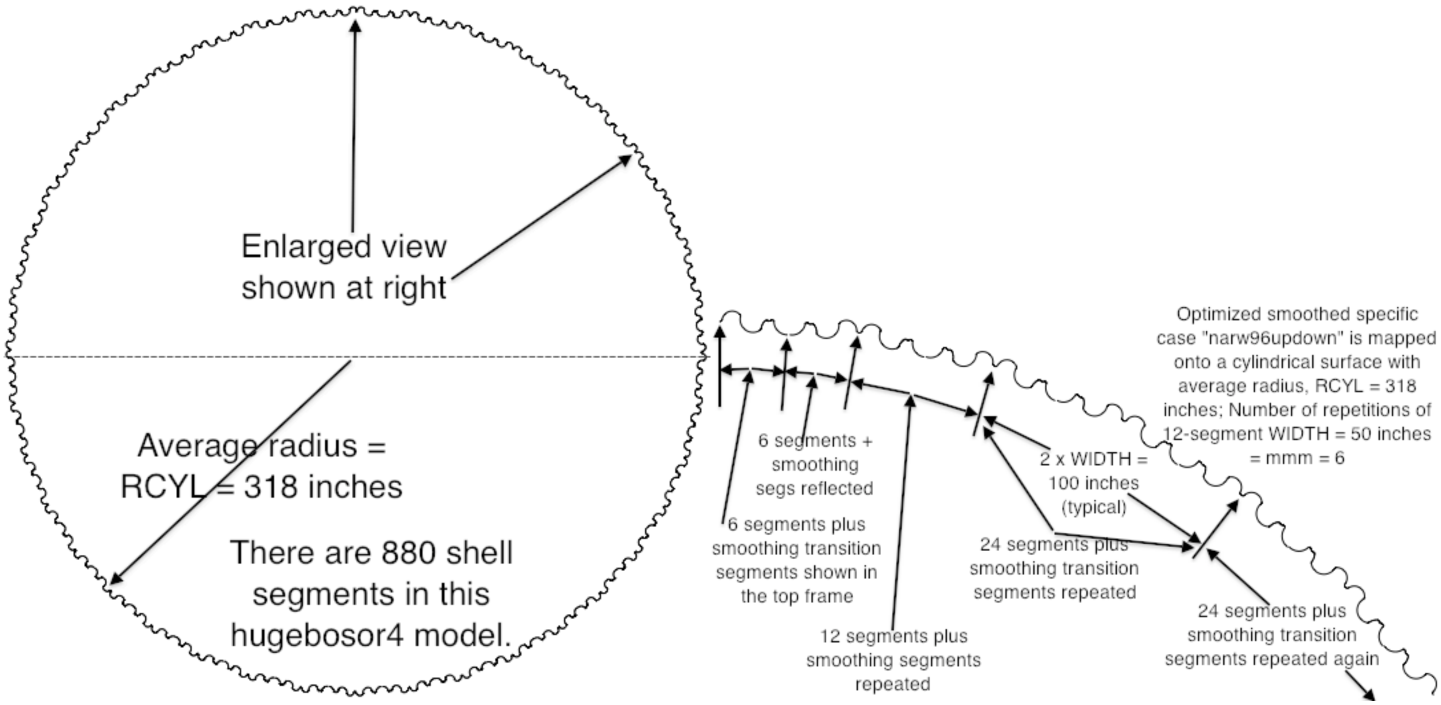


Fig. 51 STAGS model (top left, top right, and middle frames) of the specific case "**narw96updown**" with smoothing, and the predicted buckling mode shape and load factor from STAGS. There is very good agreement between the predictions of STAGS and GENOPT/BIGBOSOR4. (See Fig. 49 for the BIGBOSOR4 results.)



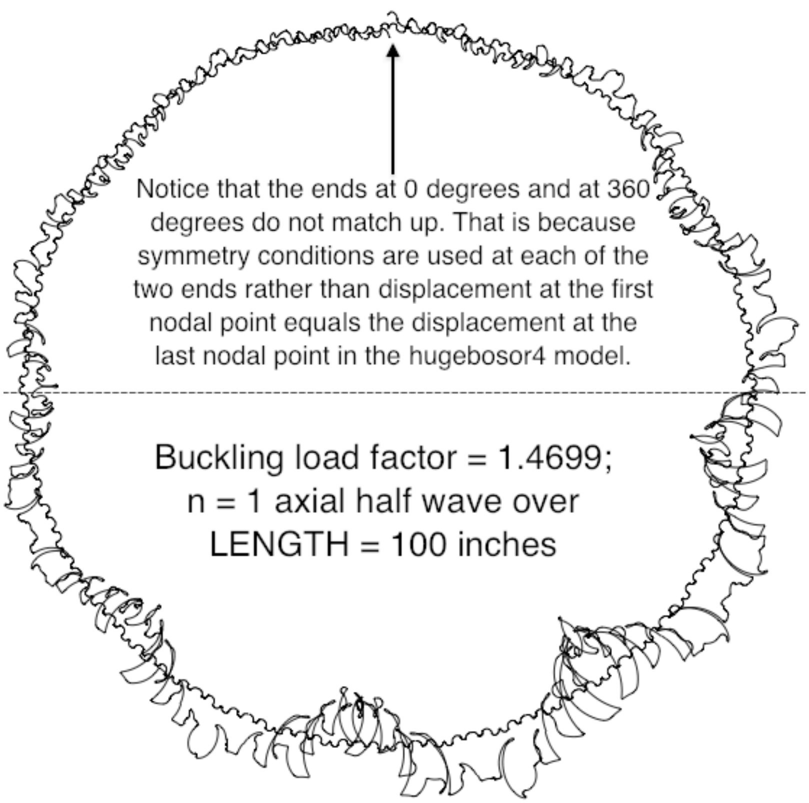


Fig. 52 GENOPT/HUGEBOSOR4 specific case **narw96updown with smoothing**: a 360-degree cylindrical shell processed via **bosdec.span9.smoothing.huge** and **hugebosor4**.

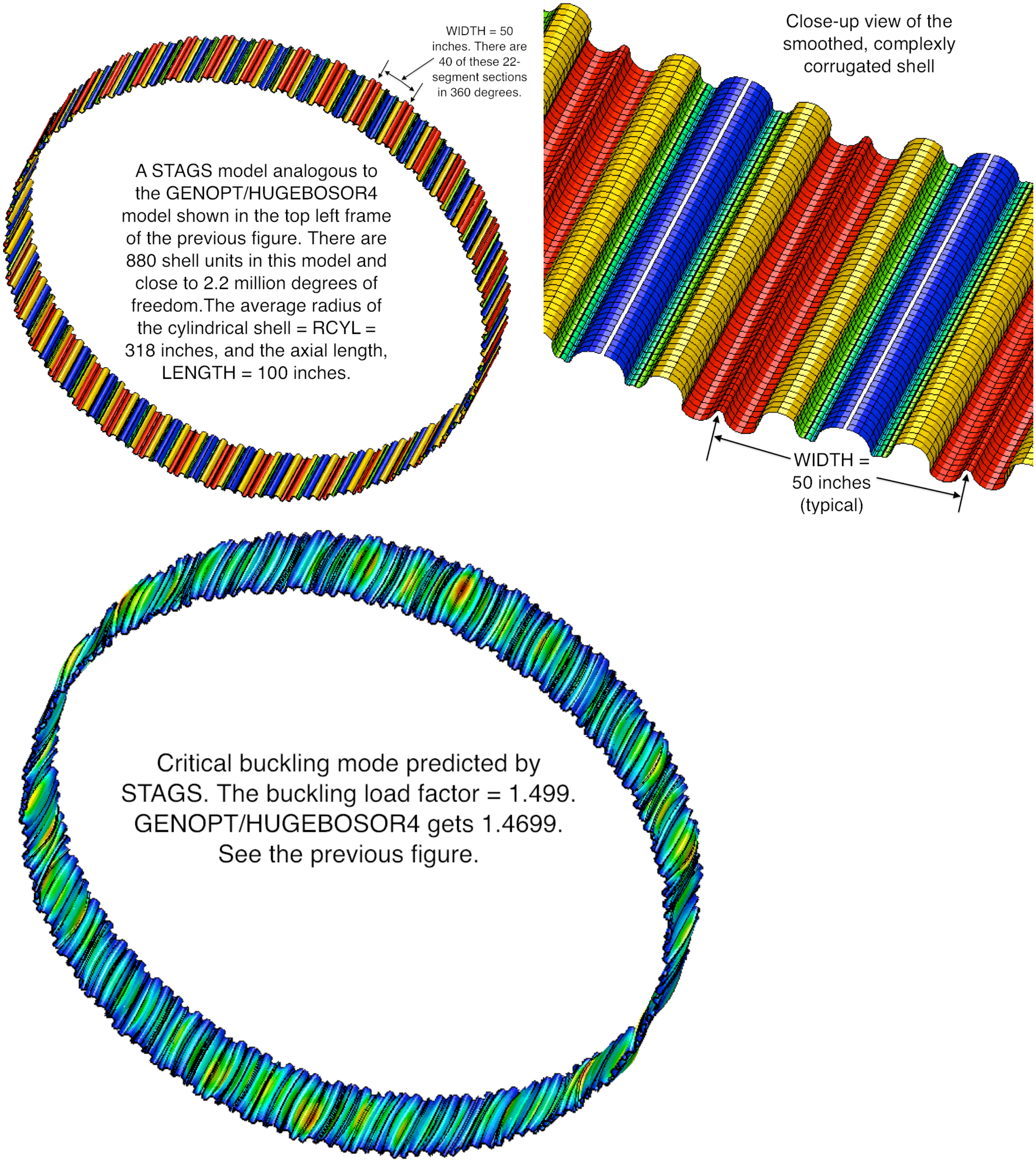


Fig. 53 Top two frames: **The huge STAGS model** of the optimized specific case, **narw96updown with smoothing**. Bottom frame: the critical buckling mode and load factor, 1.499. Compare with the bottom frame in the previous figure. There is good agreement between the predictions of STAGS and HUGEBOSOR4.

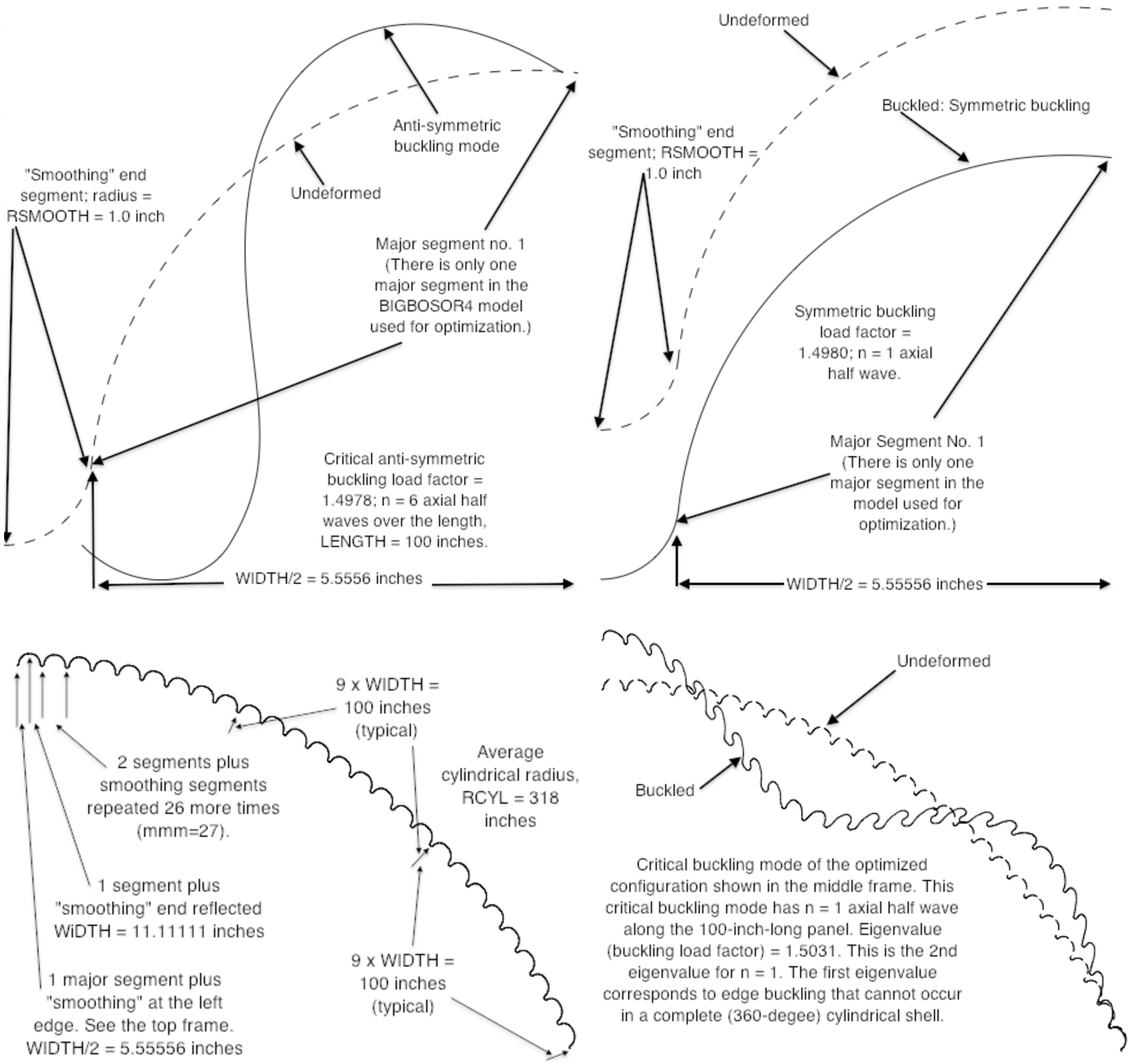


Fig. 54 Results for the specific case called "**narw91updown**" with 9 major segments per 50-inch width. (See Table 6 for dimensions, margins, and objective.) This configuration is associated with the smallest weight (92.43 lb, Table 6) plotted in Fig. 46 with solid square data points. (See the data point for "Number of segments spanning 50 inches" = 9.) **Top left frame:** Optimized profile and the critical **anti-symmetric** general buckling mode (BEHX32). Buckling load factor=1.4978 (n=6). **Top right frame:** Optimized profile and the critical **symmetric** general buckling mode (BEHX2). Buckling load factor=1.4980 (n=1). **Bottom left frame:** The optimized profile shown in the top two frames is expanded and mapped onto a cylindrical surface. **Bottom right frame:** Critical buckling mode and load factor (1.5031) of the expanded and cylindrically mapped profile.

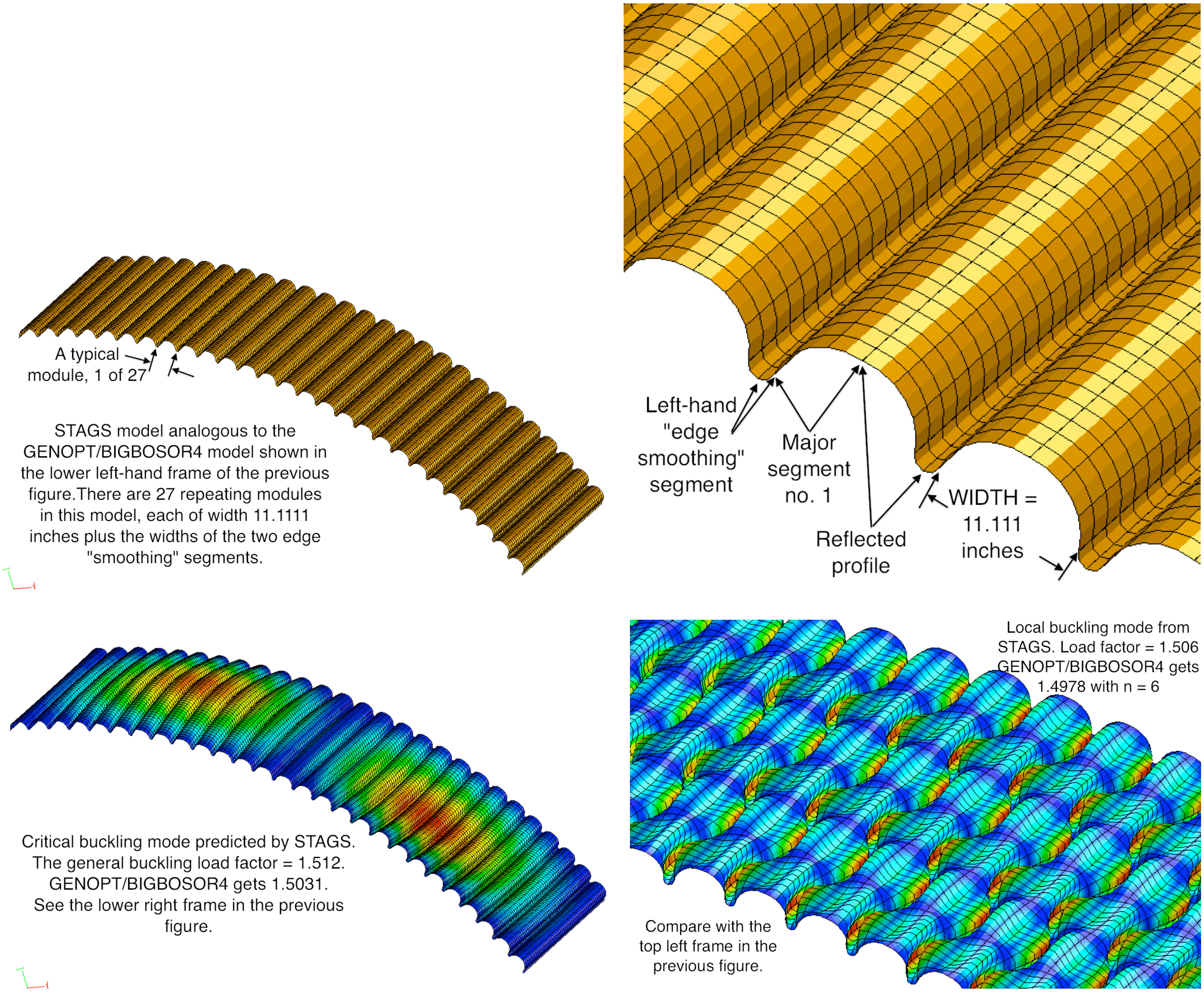


Fig. 55 **Top two frames:** The STAGS model of the optimized specific case, **narw91updown**, smoothed with 9 major segments over a width of 50 inches (solid square data point in Fig. 46) plus the accumulated widths of "edge smoothing" segments.
Bottom left-hand frame: The critical **general buckling** mode and load factor, 1.512. Compare with the bottom right-hand frame in the previous figure.
Bottom right-hand frame: Enlarged view of the critical **local buckling** mode and load factor, 1.506, STAGS predicts 6 axial half-waves over the panel length, LENGTH = 100 inches, which agrees with the BIGBOSOR4 prediction. Compare with the upper left-hand frame in the previous figure.
The first 5 eigenvalues from the STAGS model shown in the top two frames are as follows:
1.506080 (local buckling, bottom right frame), 1.507613 (local buckling), 1.510155 (local buckling), 1.511830 (general buckling, bottom left frame), 1.511931 (general buckling).

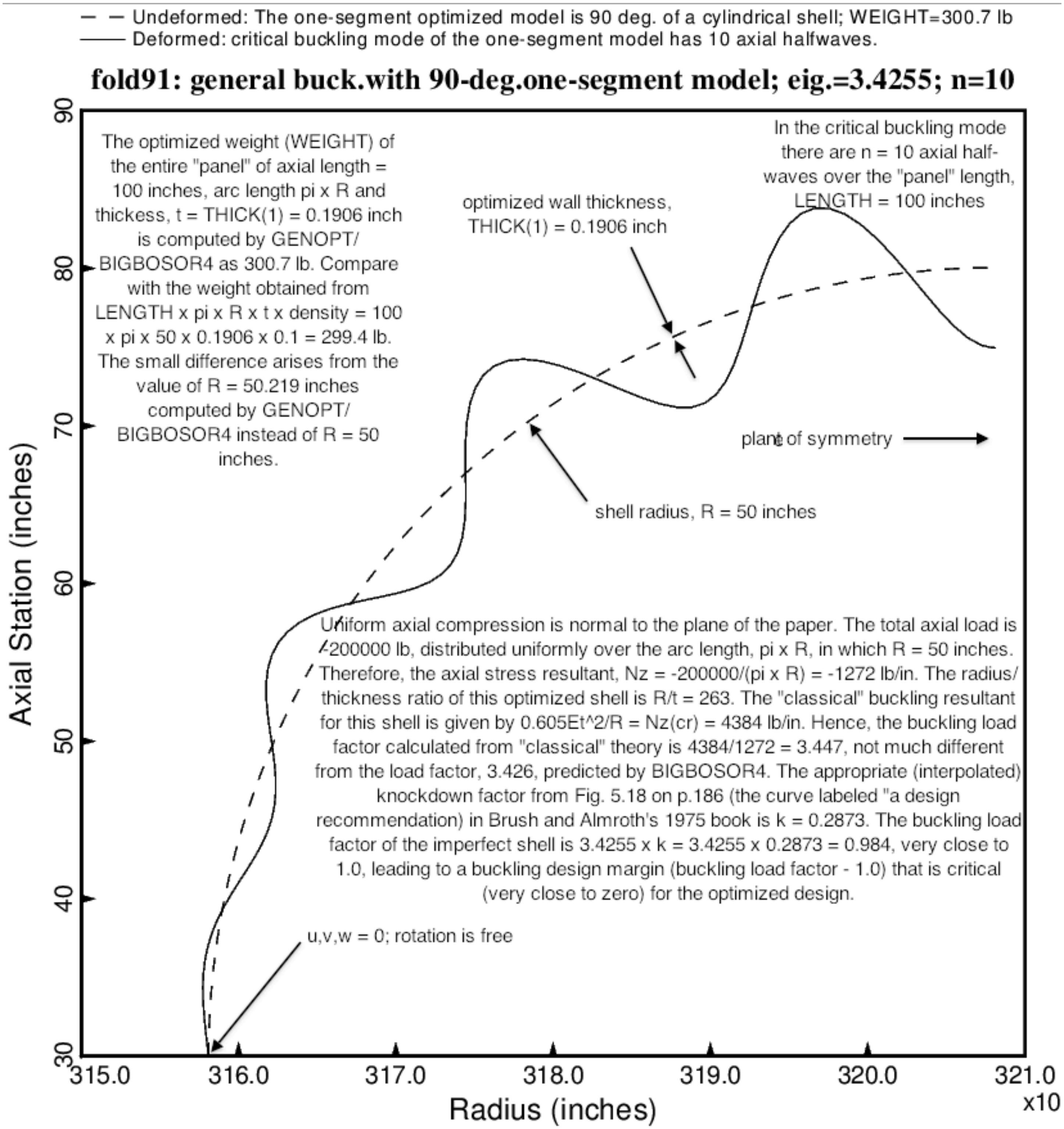


Fig. A1 "General" buckling of a model that simulates the buckling of a perfect uniformly axially compressed cylindrical shell. There is one major segment spanning half the 100-inch width (WIDTH) of the "panel". Symmetry is imposed at the symmetry plane at the right-hand edge of this model.

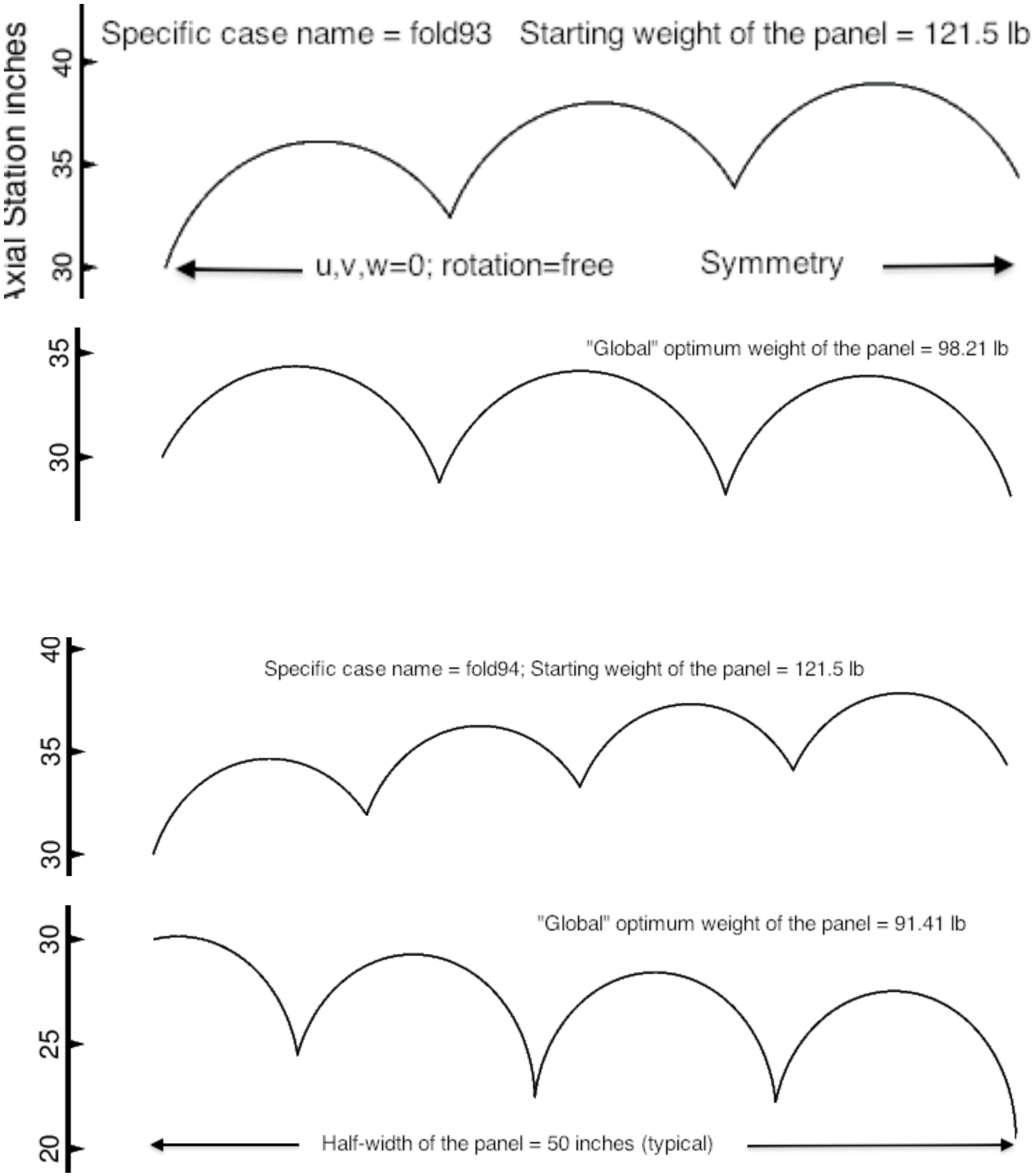


Fig. A2 Starting and optimized designs of the corrugated panels, fold93 and fold94. The thickness is uniform over the entire panel, and the corrugations are all "convex surface up", an impractical design. The "**OLD**" boundary conditions (Section 4) are used for optimization and analysis (Figs. A2 - A12).

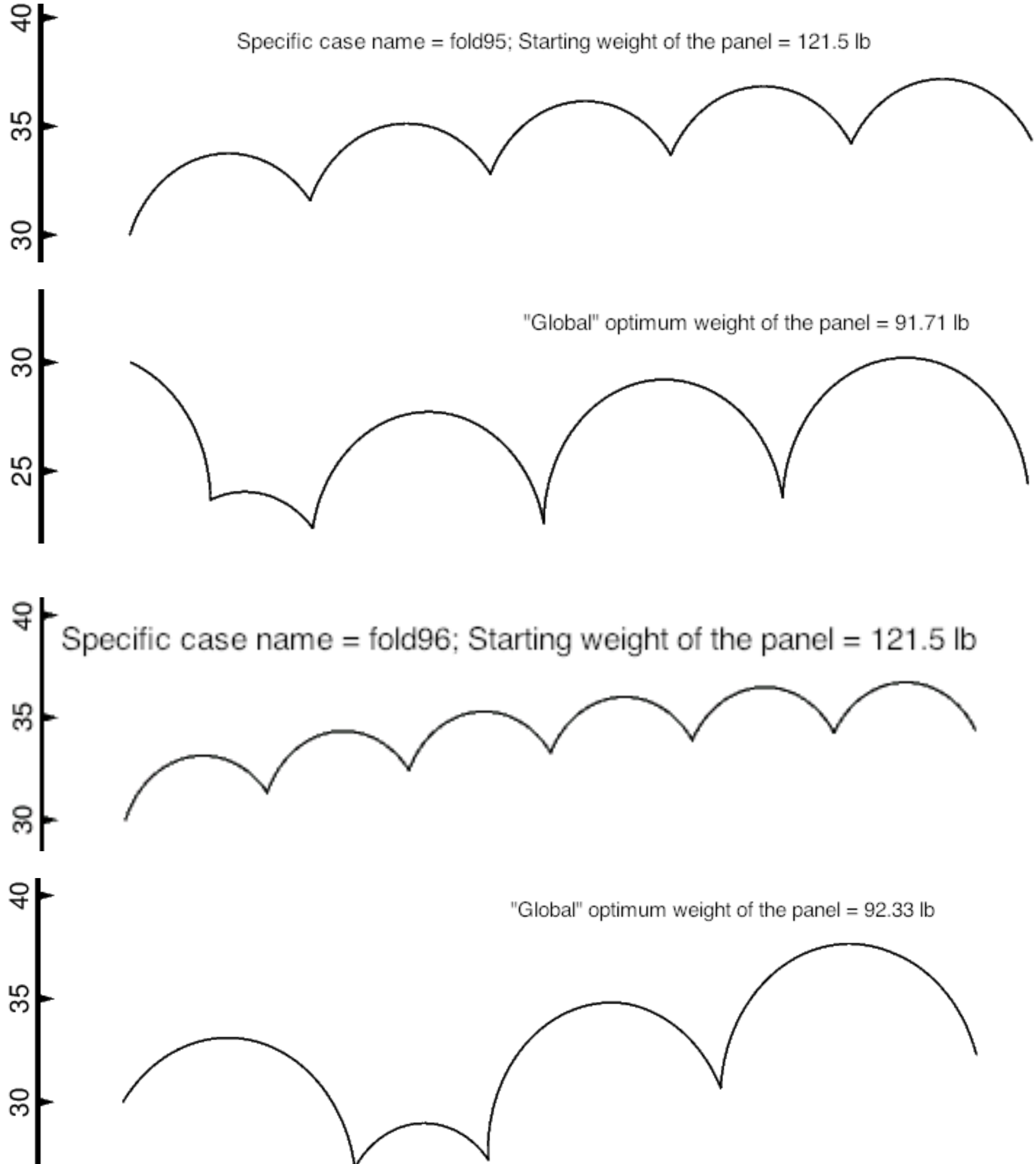


Fig. A3 Starting and optimized designs of the corrugated panels, fold95 and fold96.

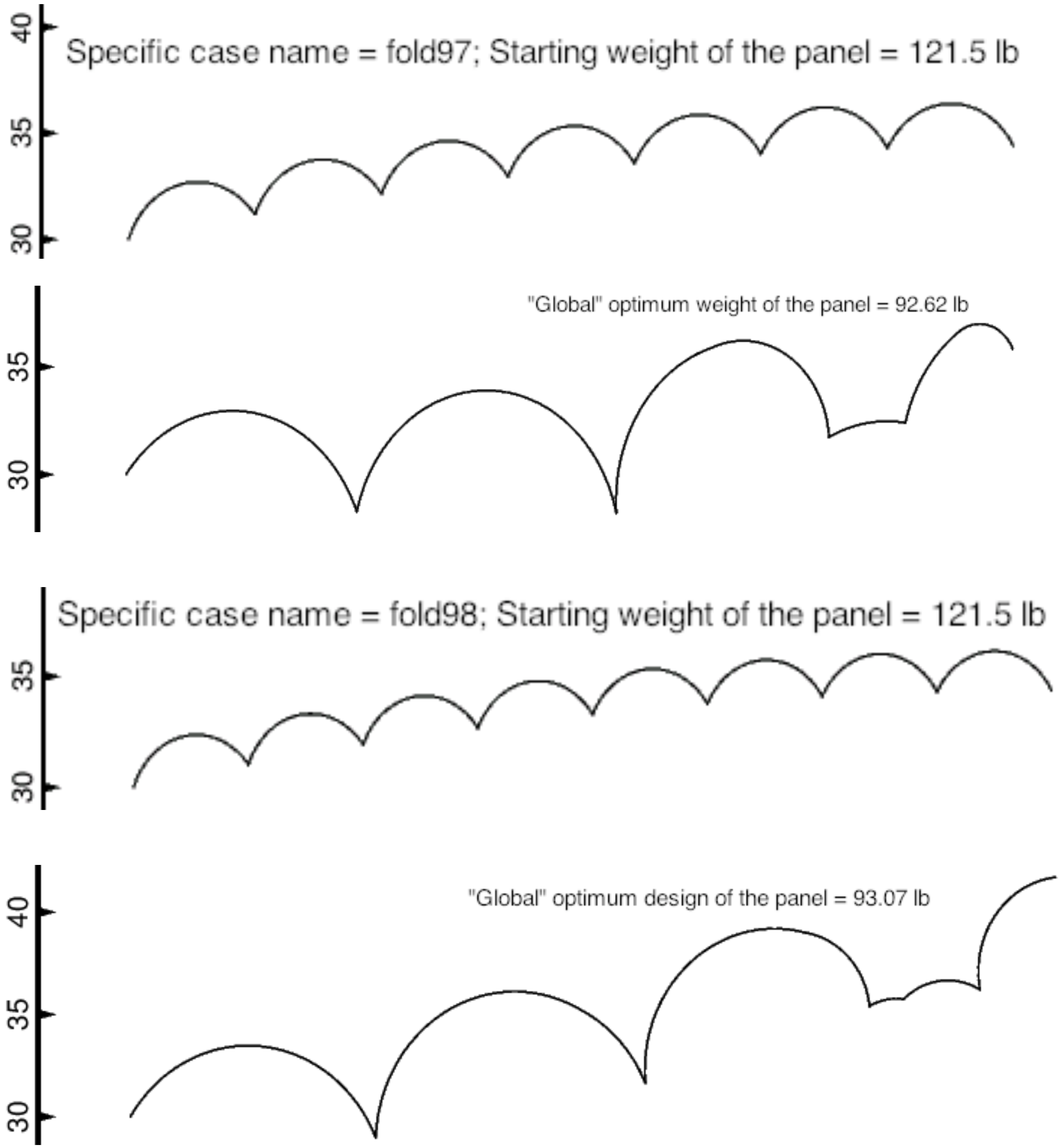


Fig. A4 Starting and optimized designs of the corrugated panels, fold97 and fold98. The thickness is uniform over the entire panel, and the corrugations are all “convex surface up”.

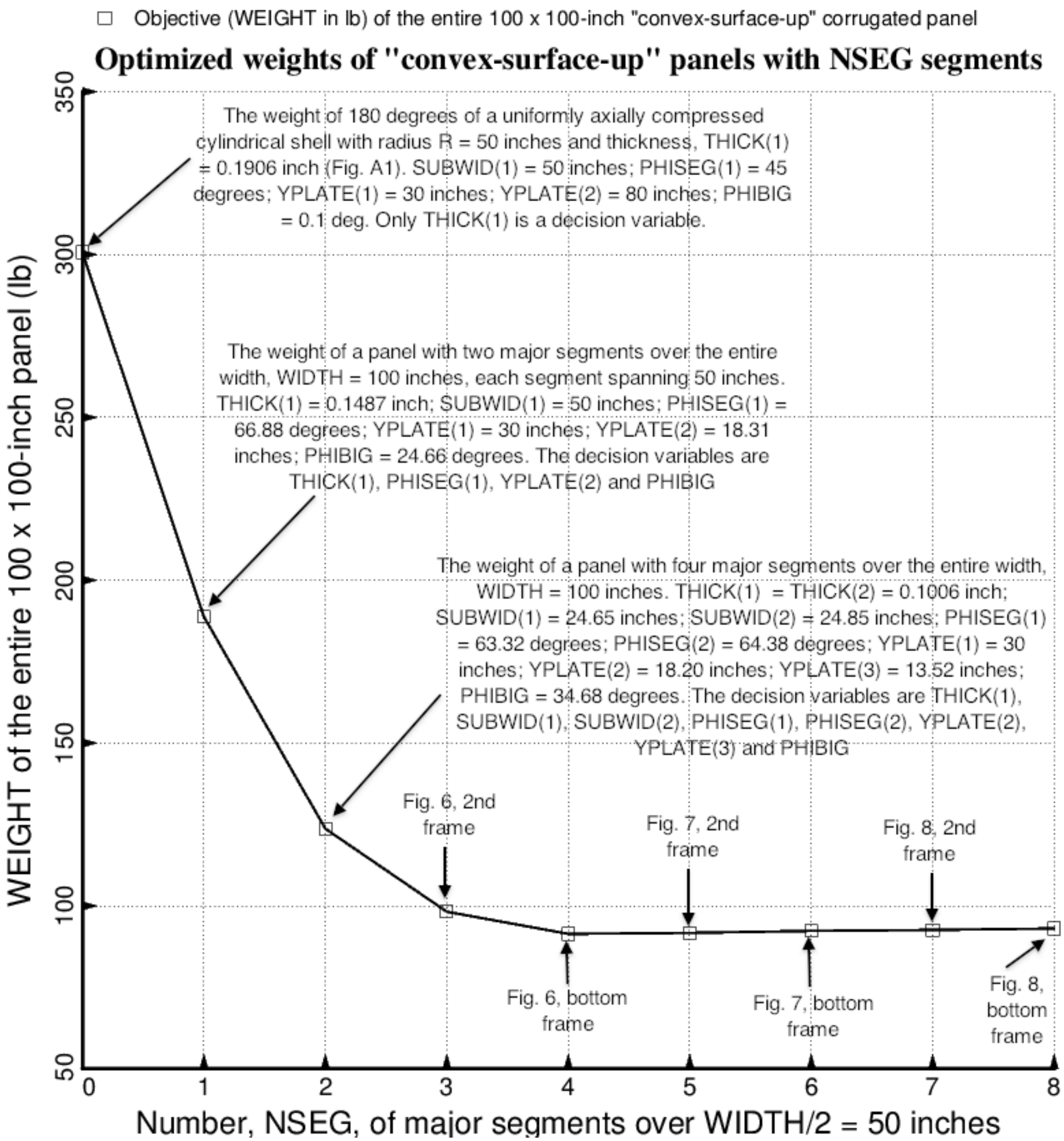


Fig. A5 Total optimized weight of the 100 x 100-inch panel as a function of the number, NSEG, of major segments over half of the panel width, WIDTH/2 = 50 inches. All of the major segments are "convex surface up". The optimized weight levels off as a function of NSEG for NSEG > 4 because several of the major segments merge into fewer, larger segments, yielding optimized designs that resemble the optimum design for NSEG = 4. The labels, Fig. 6 – 8, have been changed: Fig. 6 is now Fig. A2; Fig. 7 is now Fig. A3; Fig. 8 is now Fig. A4. The "**OLD**" boundary conditions (Section 4) are used for the optimization and analysis.

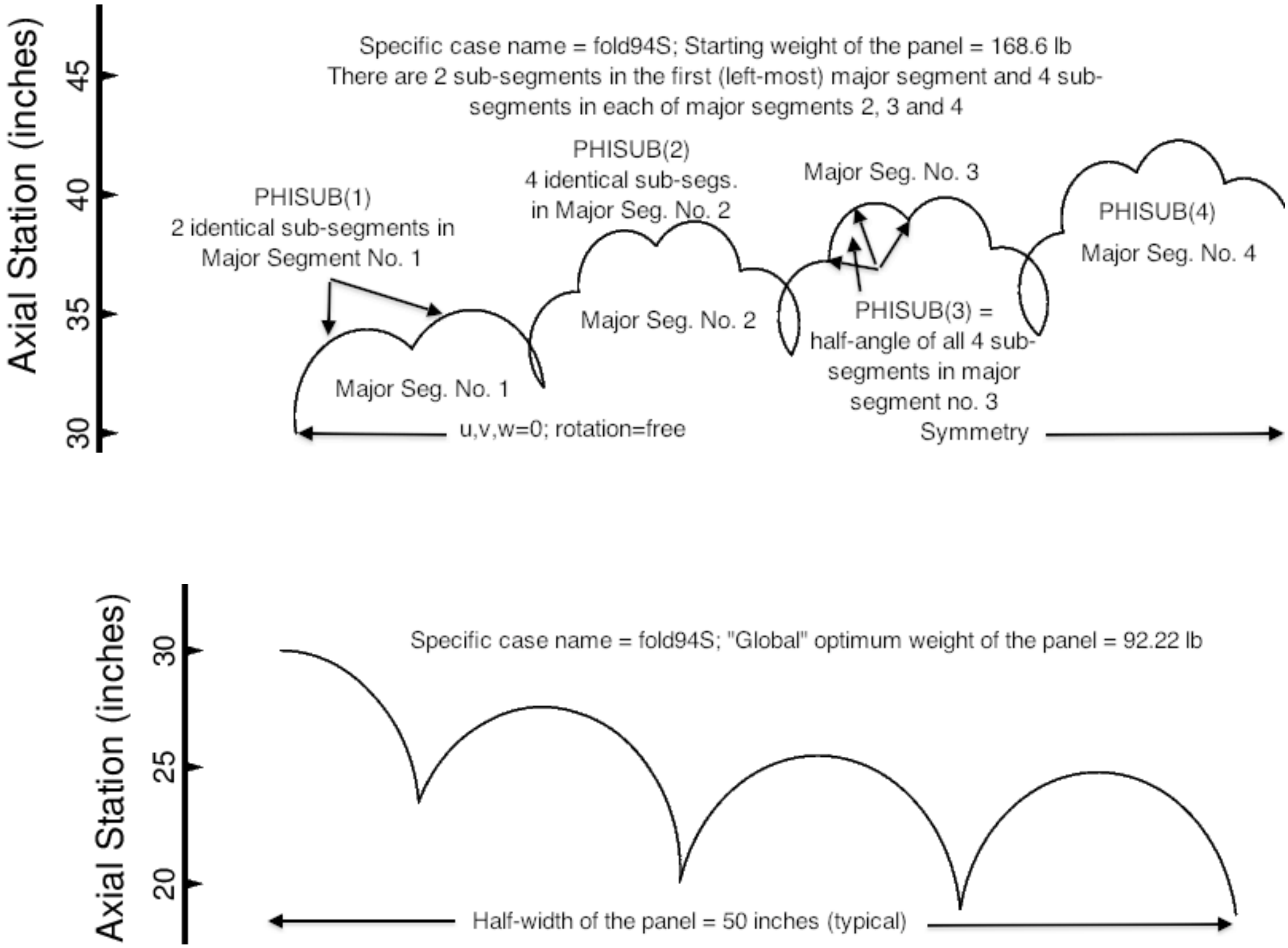
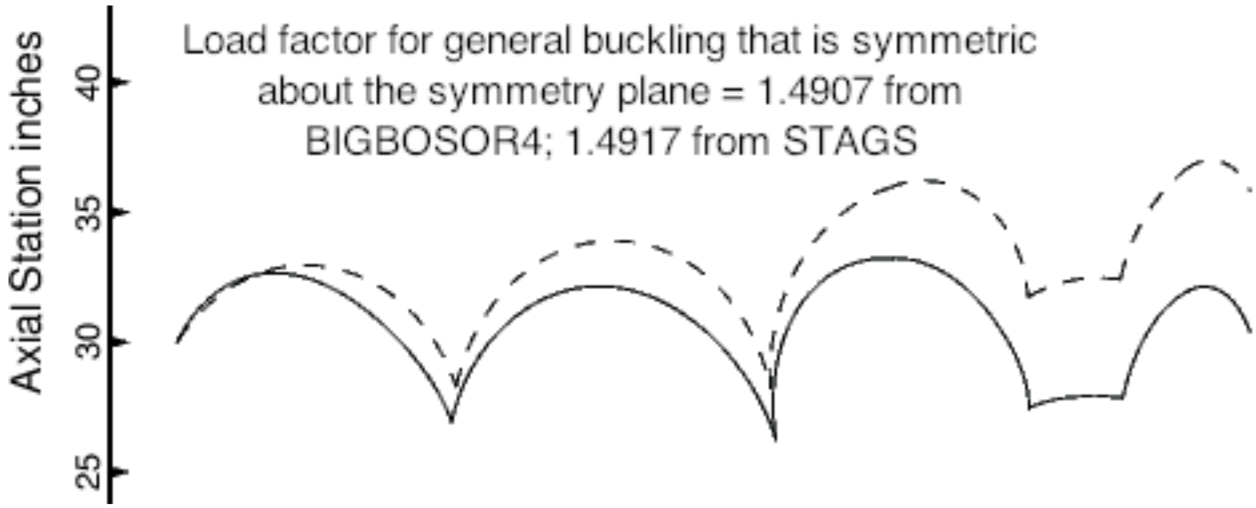


Fig. A6 Specific case = fold94S: Corrugated panel with 4 major segments, 2 sub-segments in Major Segment No. 1 (the left-most major segment) and 4 sub-segments in each of Major Segment Nos. 2, 3 and 4. Only half the panel width is shown, with symmetry conditions existing on the right-hand side of the model. Compare the optimized cross-section shown in the bottom frame here with that displayed in the bottom frame of Fig. A2, which shows results for the specific case called “fold94” in which 0 sub-segments are specified for every major segment. The “**OLD**” boundary conditions (Section 4) are used for the optimization and analysis.



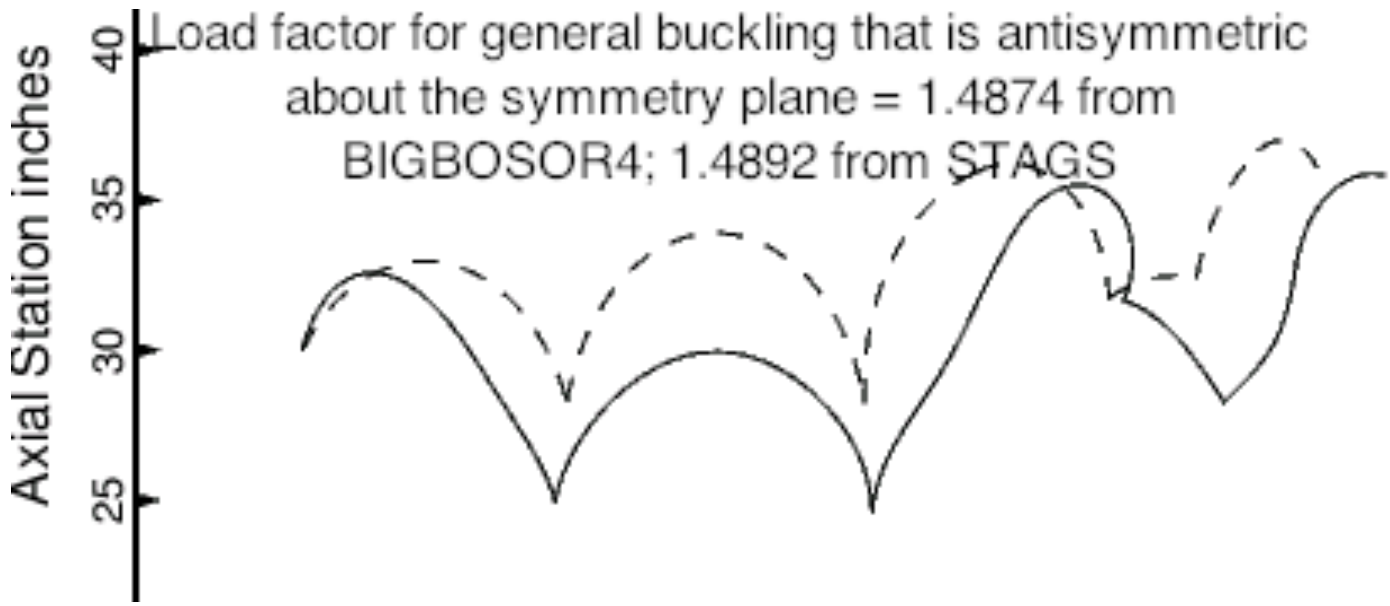


Fig. A7 Specific case name = fold97. General buckling of the optimized corrugated panel predicted by BIGBOSOR4 for general buckling that is symmetric with respect to the symmetry plane at x = WIDTH/2 (top) and for general buckling that is antisymmetric with respect to the symmetry plane (bottom). The general buckling mode corresponding to the critical (lowest) buckling load factor has n = 1 half-wave over the 100-inch axial length of the panel. The axial coordinate direction is normal to the plane of the paper. The "**OLD**" boundary conditions (Section 4) are used for the optimization and analysis.

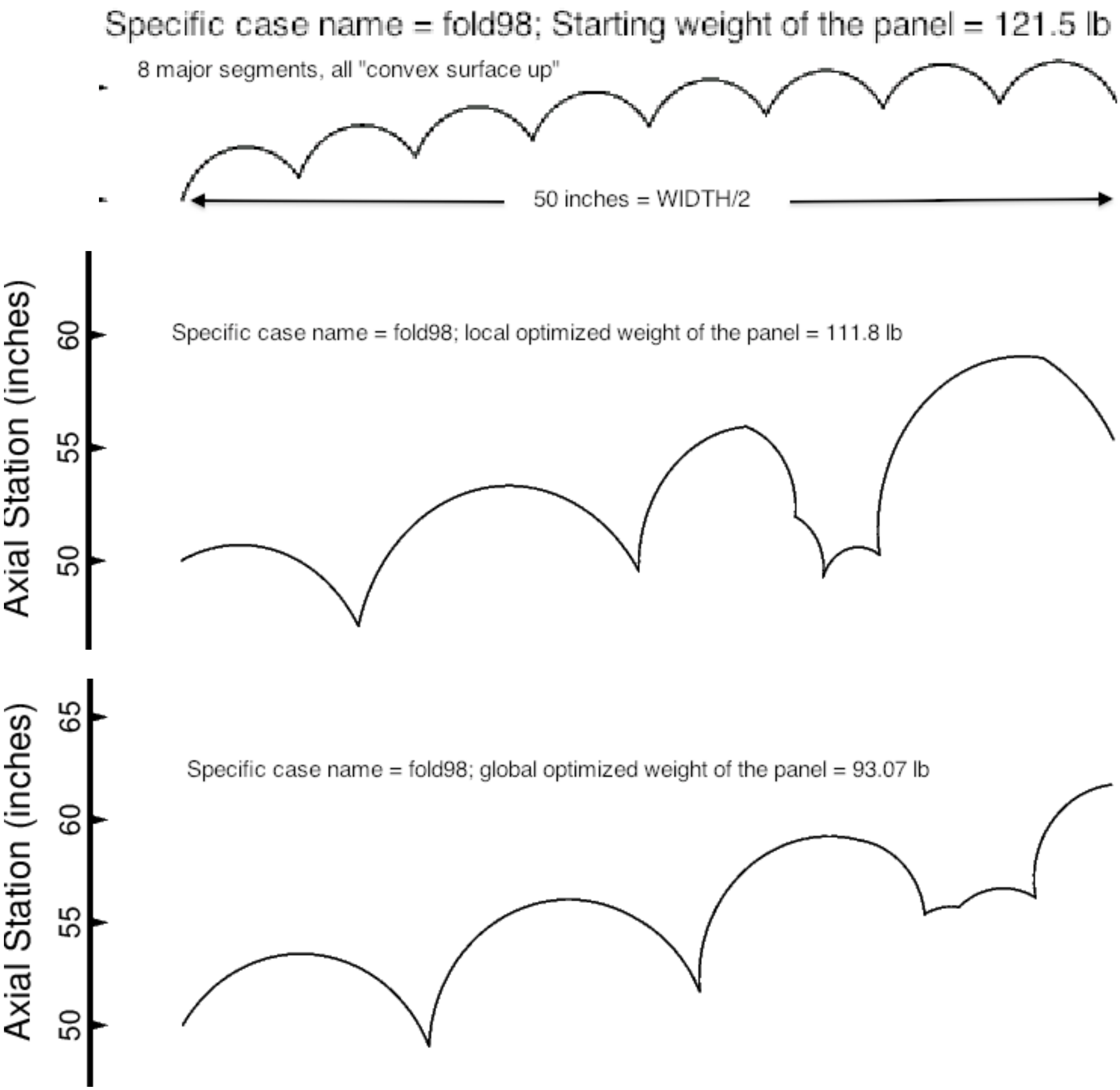


Fig. A8 Specific case called "fold98". Starting design of the panel with WIDTH = 100 inches (top); First optimized design determined via SUPERDUPEROPT with six sequential executions of SUPEROPT (middle); Second optimized design determined via several separate executions of SUPEROPT with the use of various strategy parameters, IMOVE, IAUTOF, and number of OPTIMZE executions per execution of AUTOCHANGE (bottom). **This figure demonstrates the difficulty that GENOPT/BIGBOSOR4 has in determining a "global" optimum design.** "Global" is enclosed in quotation marks because GENOPT cannot rigorously determine a global optimum design, but attempts to get close via optimization cycles that begin from many different points in design space for each execution of SUPEROPT. (See Figs. 4 and 5, for example).

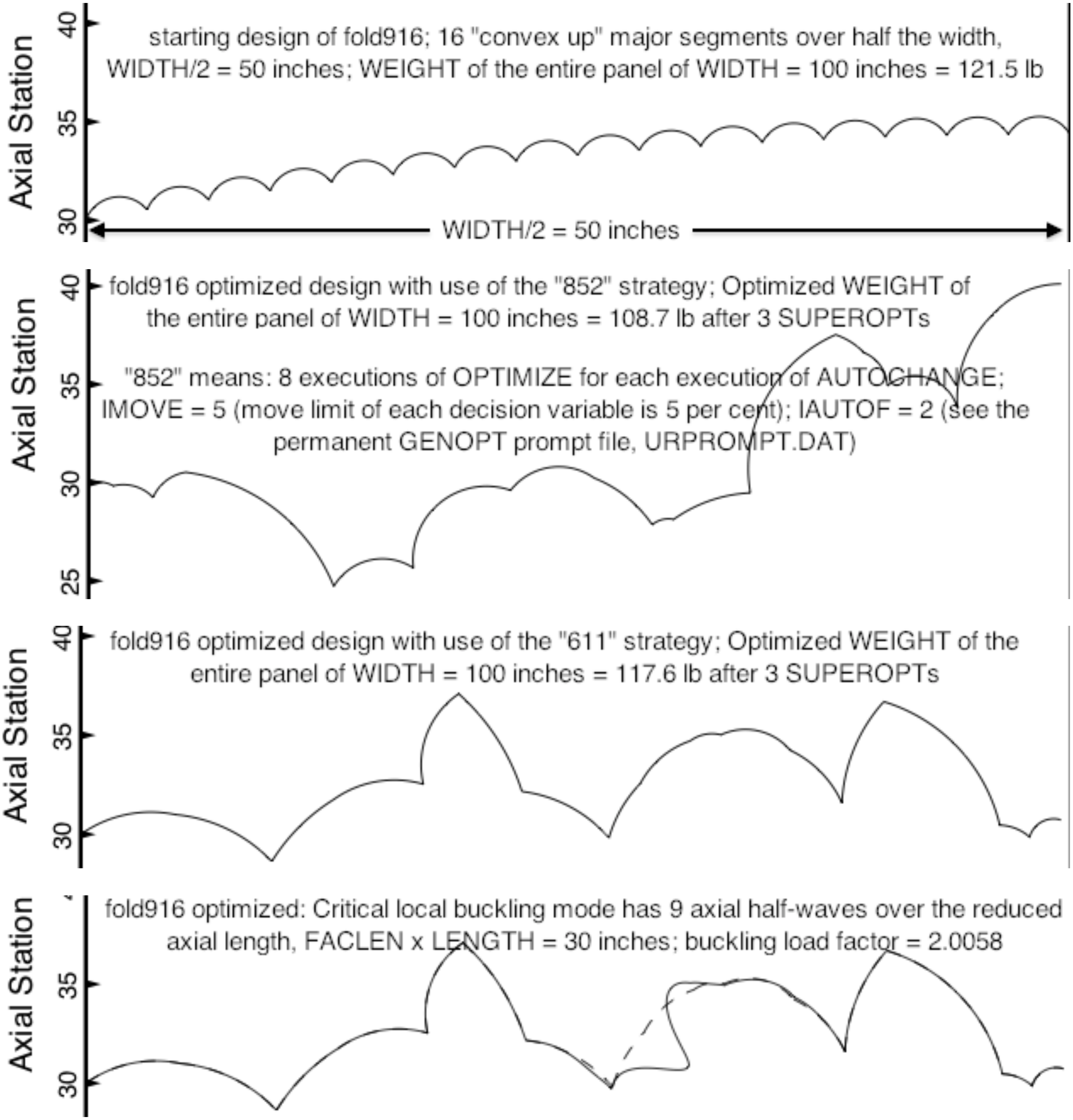


Fig. A9 Specific case called "fold916": Top: starting design; 2nd: Optimized design with use of "852" strategy; 3rd: Optimized design with use of the "611" strategy (6 optimizes/autochange. IMOVE=1, IAUTOF=1); Bottom: Local buckling of the "611" optimized panel. The "**OLD**" boundary conditions (Section 4) are used.

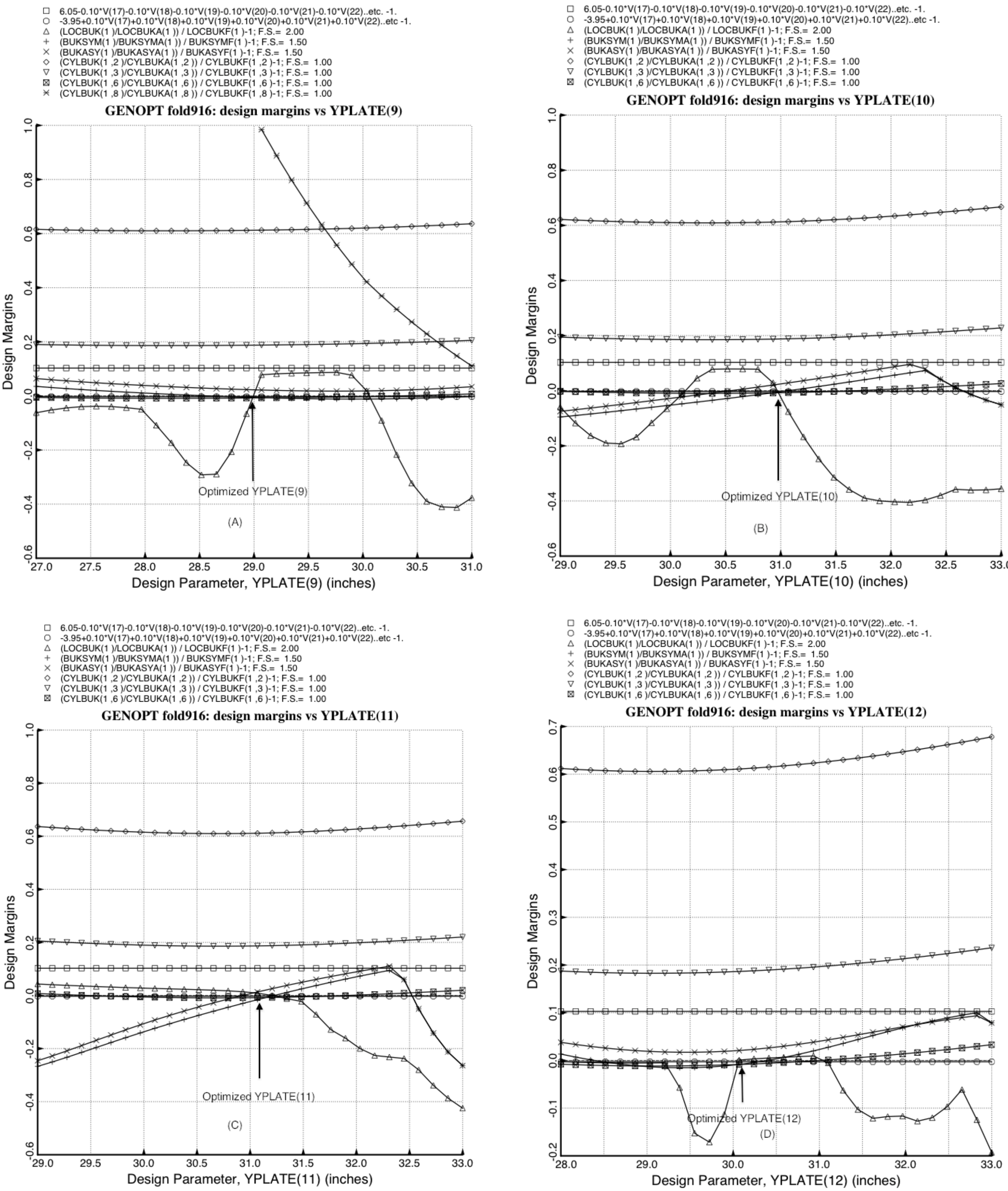


Fig. A10 Sensitivity of the optimized “611” **“fold916”** design to YPLATE(j), j =9 (A), 10 (B), 11 (C), 12 (D)

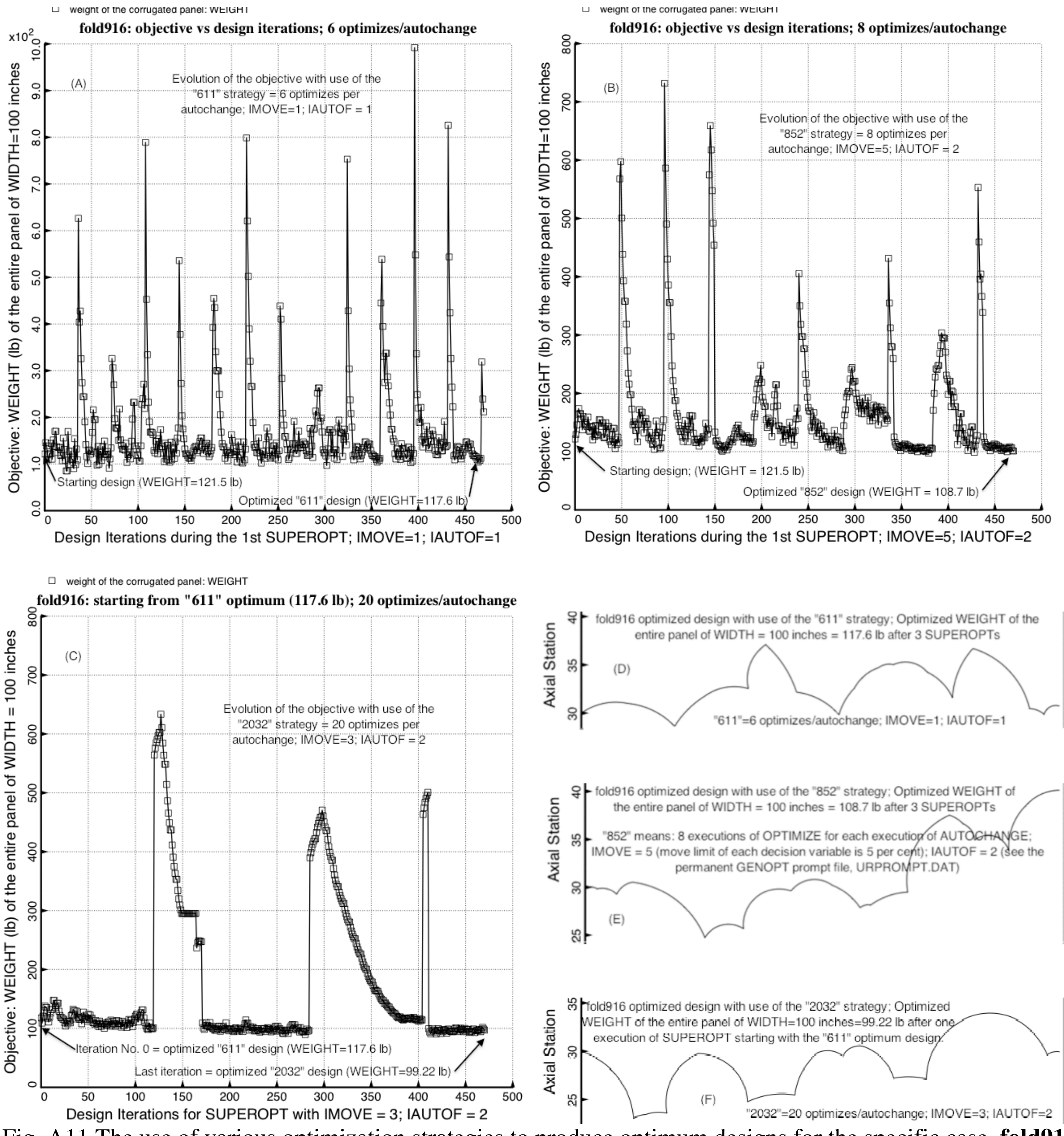


Fig. A11 The use of various optimization strategies to produce optimum designs for the specific case, **fold916**:
(A) = optimization with use of the "611" strategy (6 optimizes/autochange; IMOVE=1; IAUTOF=1)
(B) = optimization with use of the "852" strategy (8 optimizes/autochange; IMOVE=5; IAUTOF=2)
(C) = optimization with use of the "2032" strategy (20 optimizes/autochange; IMOVE=3; IAUTOF=2)
(D, E, F) = The three different optimum designs corresponding to the three different optimization strategies.

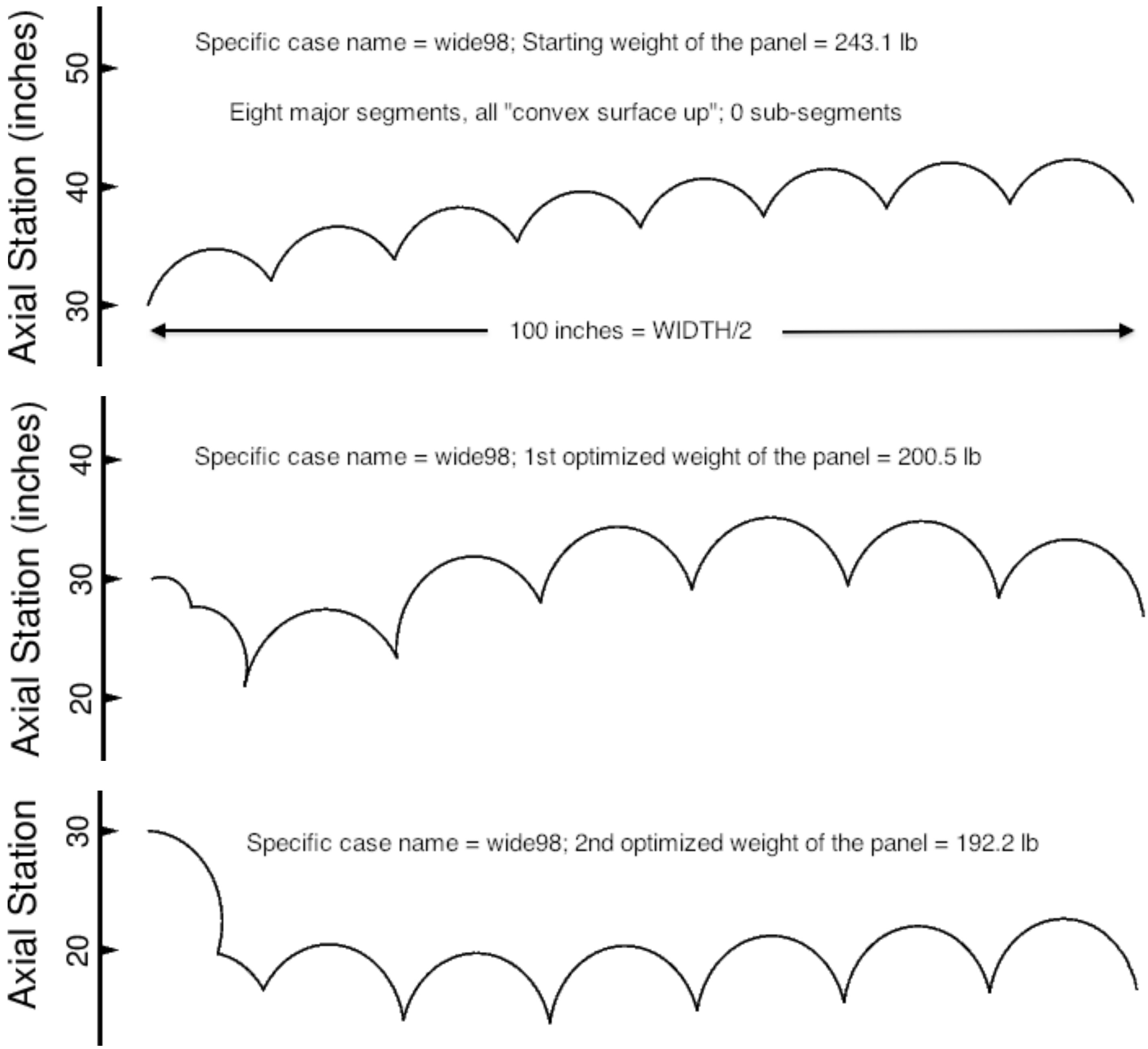


Fig. A12 Specific case called **"wide98"**. Starting design of the panel with WIDTH = 200 inches (top); First optimized design determined via SUPERDUPEROPT with six sequential executions of SUPEROPT (middle); Second optimized design determined via several separate executions of SUPEROPT with the use of various strategy parameters, IMOVE, IAUTOF, and number of OPTIMZE executions per execution of AUTOCHANGE (bottom). This figure demonstrates the difficulty that GENOPT/BIGBOSOR4 has in determining a "global" optimum design. "Global" is enclosed in quotation marks because GENOPT cannot rigorously determine a global optimum design, but attempts to get close via optimization cycles that begin from many different points in design space for each execution of SUPEROPT. (See Figs. 4 and 5, for example).

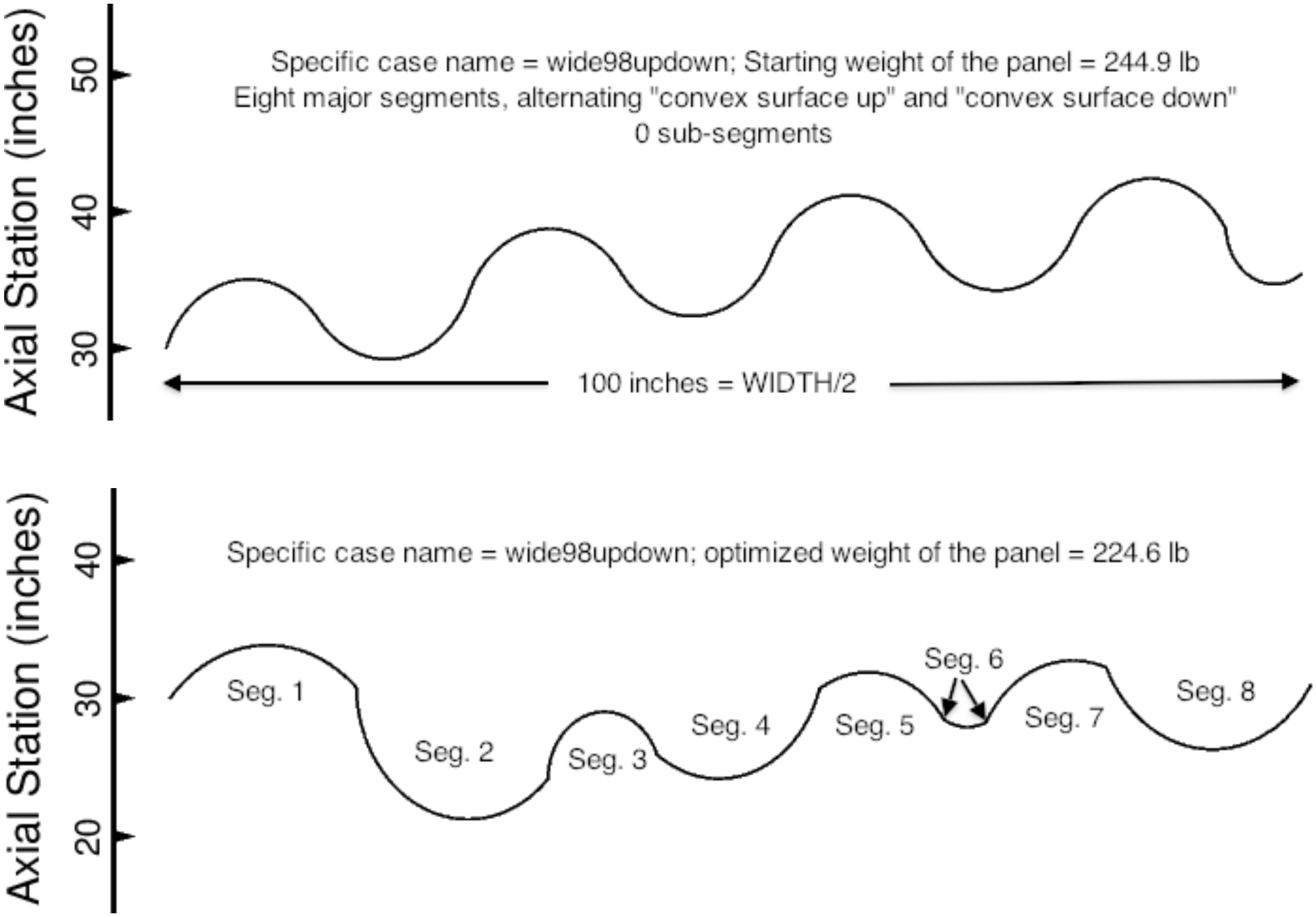


Fig. A13 Specific case called "wide98updown". Starting design of the panel with WIDTH = 200 inches (top); Optimized design determined via SUPERDUPEROPT with six sequential executions of SUPEROPT (bottom). The specific weight of this wider panel (weight per unit width) is significantly greater (224.6/200 = 1.123 lb/inch) than that for the panel with half the width (Fig. 6), which is 92.69/100 = 0.9269 lb/inch, perhaps because the boundaries are further apart, perhaps because GENOPT failed to find the "global" optimum design. **NOTE: The best way to find optimized weights of wide corrugated panels via the "span9" software is to use the method demonstrated by Figs. 9 – 12:**

1. Change the boundary condition along the left-hand longitudinal edge from "u,v,w held; rotation free" (Fig. 6) to "symmetry or anti-symmetry". Use the "bosdec" file called "**bosdec.span9.leftedge**" to do this.

2. Re-optimize the half-width model with the new boundary condition along the left-hand longitudinal edge, that is, with the use of **bosdec.span9.leftedge**. (Compare the optimized weights in Fig. 6 and Fig. 9).

3. Use the file, …/genoptcase/*.**BEHX0**, which contains valid input data for the BIGBOSOR4 analysis of a multi-WIDTH wide panel with repeating previously optimized cross section profiles, as shown in the top frame of Fig. 11.

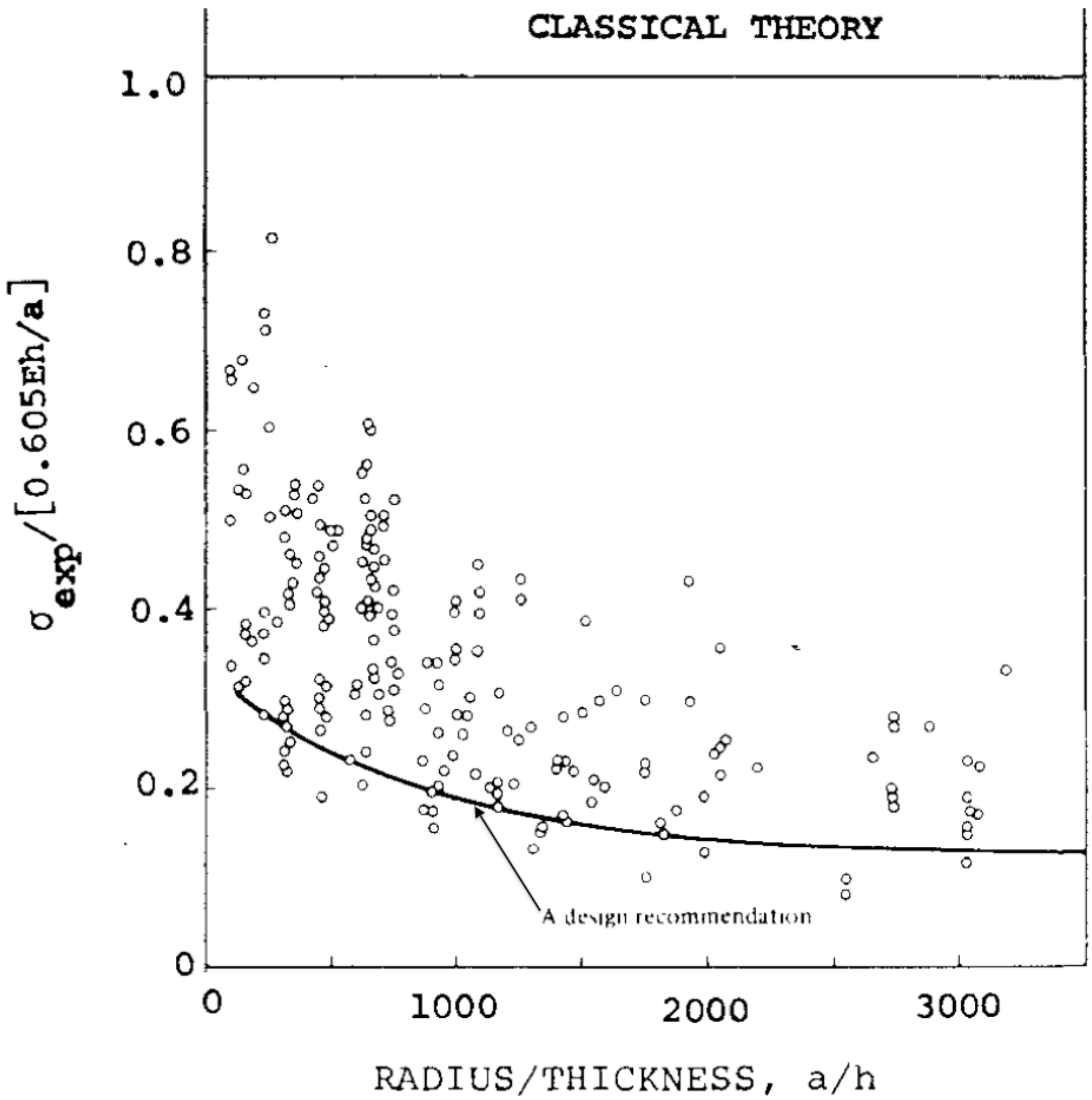


Fig. A14 Comparison between test and theory for the buckling of axially compressed cylindrical shells. "a" is the radius; h is the wall thickness; E is the Young's modulus; 0.605Eh/a is the "classical" buckling stress of a perfect shell made of isotropic material with Poisson ratio equal to 0.3; $sigma_{exp}$ is the buckling stress from tests. The normalized buckling load of the perfect shell is 1.0. Most of the test points fall far below 1.0, especially for shells with very high radius/thickness ratio, a/h. The solid line corresponds to a design recommendation in which about 95 per cent of the test results fall above the curve. (This is a modified form of Fig. 5.18, page 186 of the 1975 book by Brush & Almroth [25].)

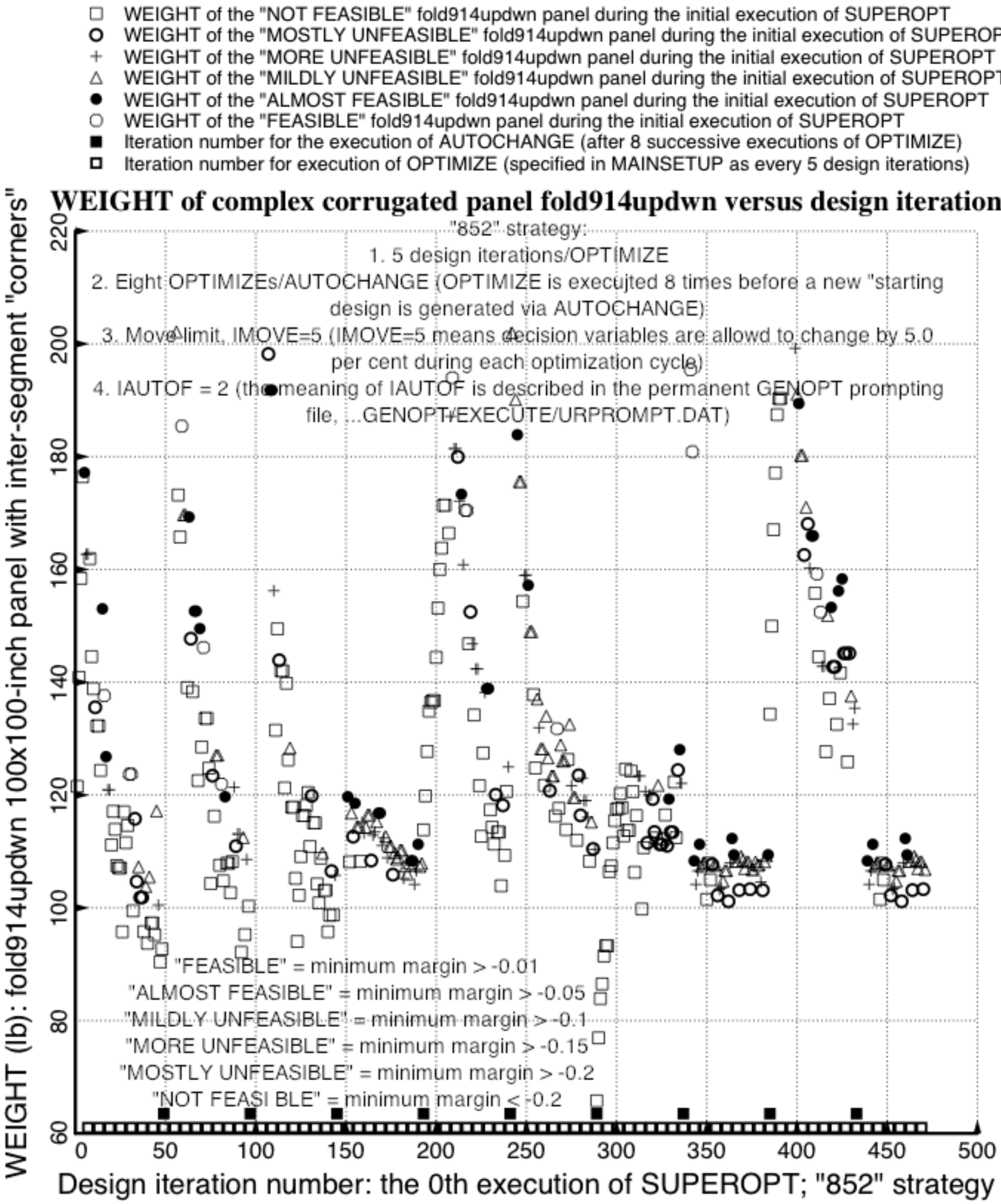


Fig. A15 The initial evolution of the objective (WEIGHT) corresponding to "**fold914updwn**" designs of various quality (NOT FEASIBLE, MOSTLY UNFEASIBLE, MORE UNFEASIBLE, etc.) during the initial execution of SUPEROPT with use of the "852" optimization strategy. There are very few "FEASIBLE" data points, and the minimum "FEASIBLE" weight is 121.9 lb. **The minimum "ALMOST FEASIBLE" weight is 108.3 lb;** The corresponding "ALMOST FEASIBLE" design is used as the starting design for the next execution of SUPEROPT, results from which appear in the next figure.

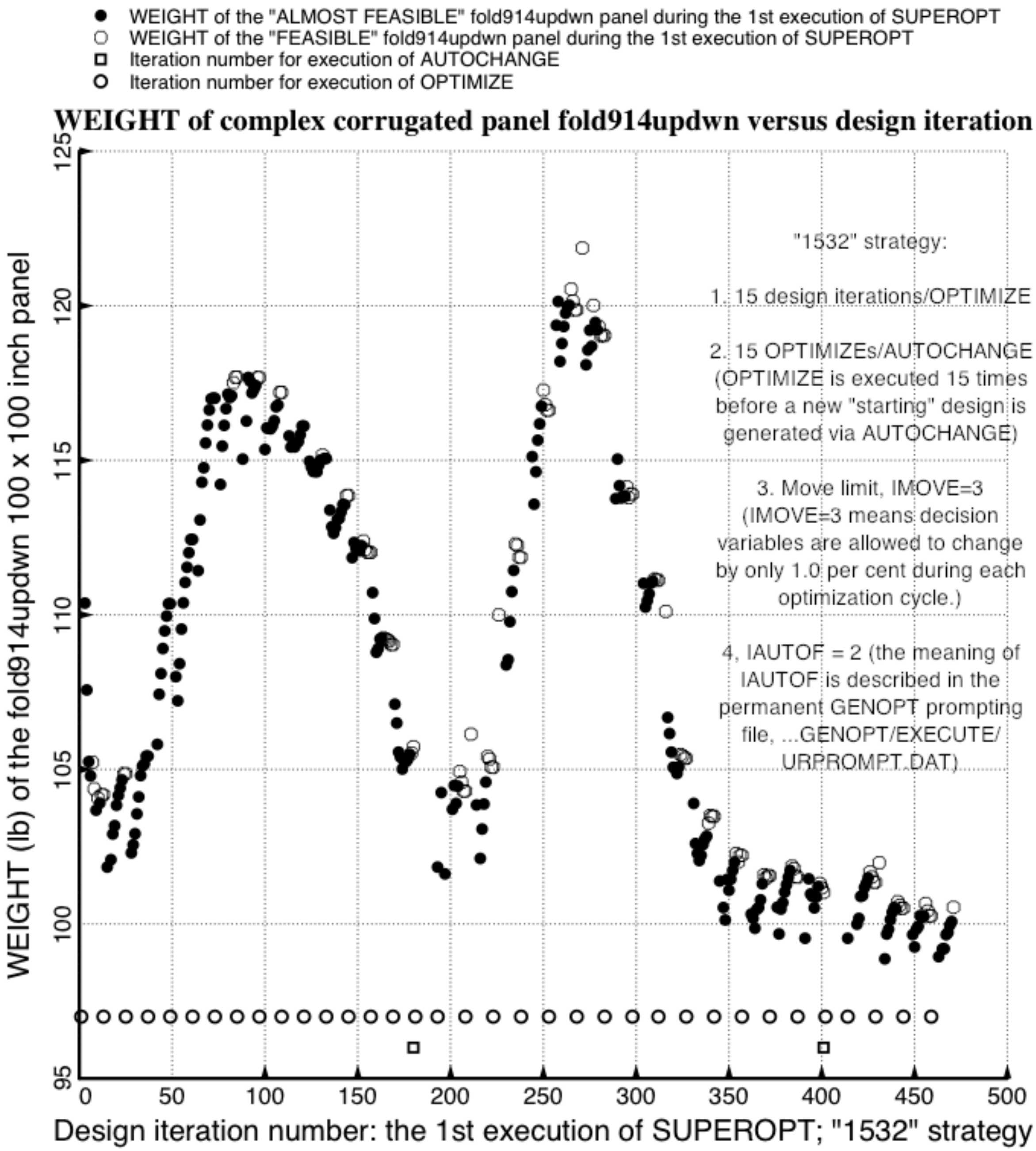


Fig. A16 The evolution of the objective (WEIGHT) corresponding to “ALMOST FEASIBLE” (black dots) and “FEASIBLE” (open dots) designs during the first execution of SUPEROPT with use of the “1532” optimization strategy immediately following a previous execution of SUPEROPT with use of the “852” strategy (previous figure). Notice that the “1532: strategy leads to many more “FEASIBLE” and “ALMOST FEASIBLE” data points than exist in the previous figure. The “1532” strategy eventually leads to a significantly lower WEIGHT (data points near the right-hand side of the plot) than that found from use of the “852” strategy. The results from continued optimization during another execution of SUPEROPT with use of the “1532” strategy are shown in the next figure, which, especially in its initial phase, exhibits a continuing decrease in the optimum WEIGHT.

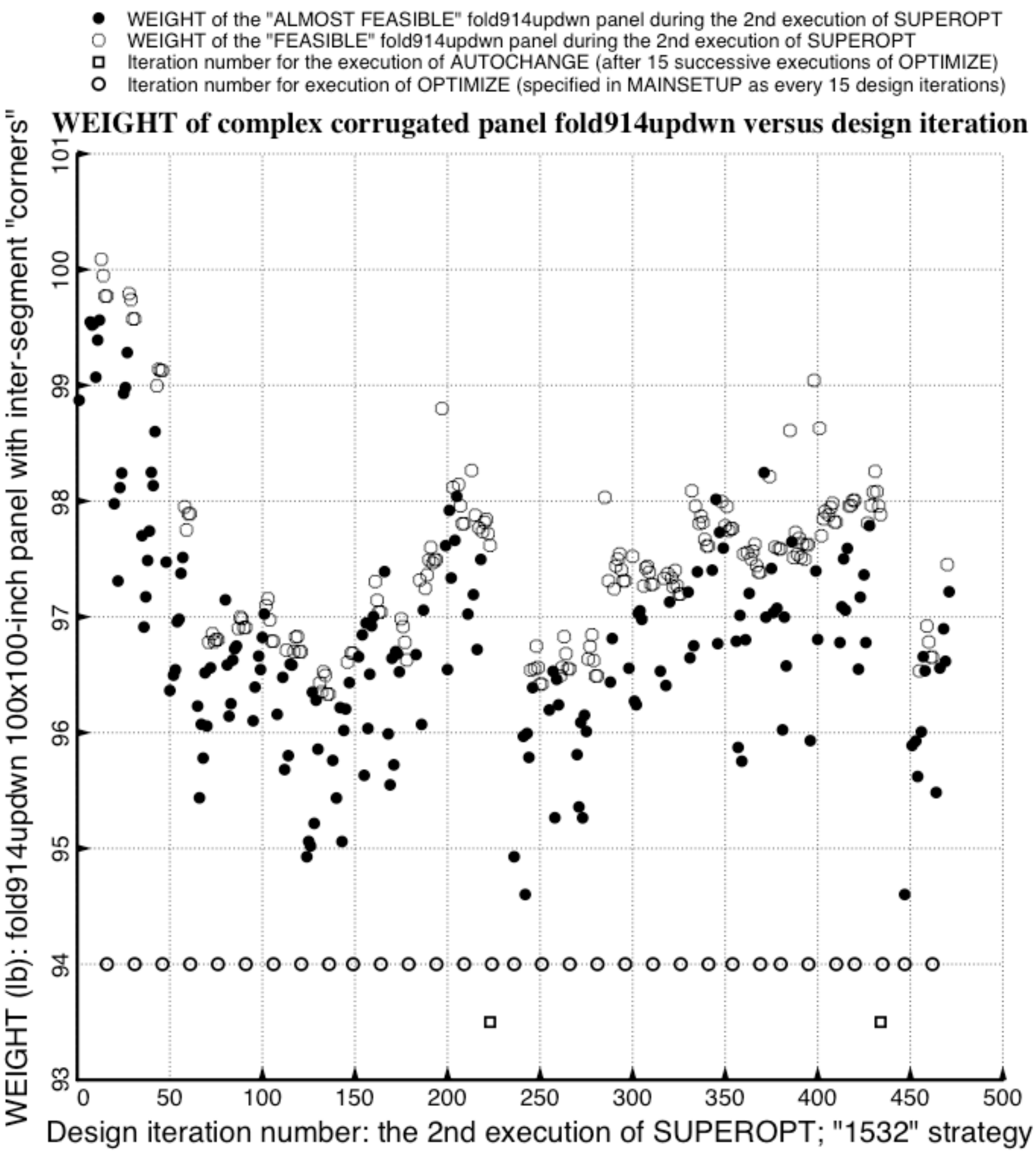


Fig. A17 The continuing evolution of the objective (WEIGHT) corresponding to “ALMOST FEASIBLE” (black dots) and “FEASIBLE” (open dots) designs during the second execution of SUPEROPT with use of the “1532” optimization strategy immediately following a previous execution of SUPEROPT, also with use of the “1532” strategy (previous figure). The continuing use of the “1532” strategy eventually leads to a significantly lower WEIGHT (some of the data points near the right-hand side of the plot) than that existing after the first execution of SUPEROPT with use of the “1532” strategy.

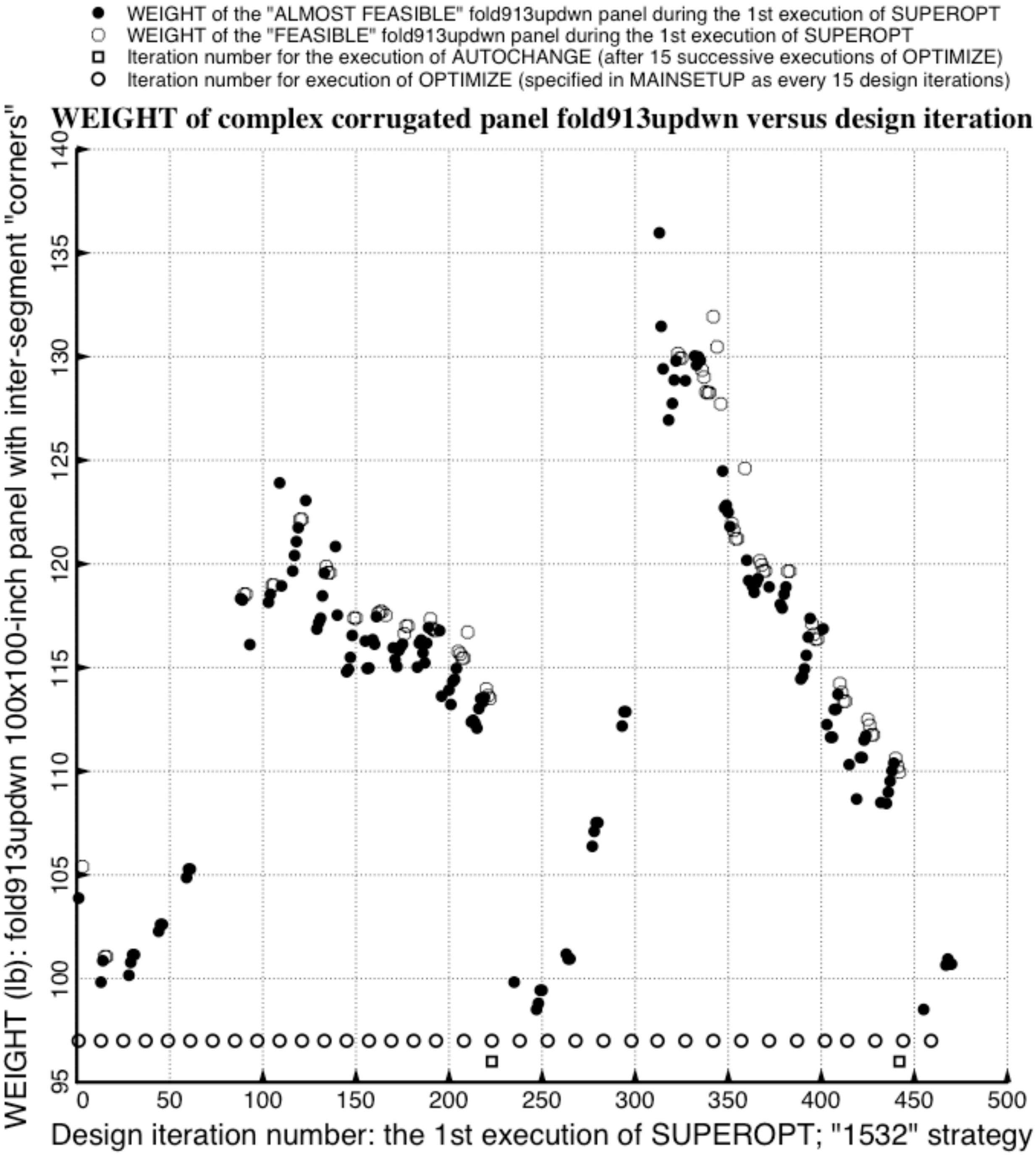


Fig. A18 **This figure is analogous to Fig. A16.** Shown here is an example in which the same strategy used in connection with the specific case called “**fold914updwn**” (Fig. A16) did not, in this different specific case called “**fold913updwn**”, lead to a “global” optimum design with a WEIGHT below 100 lb. (The “FEASIBLE” design with the lowest weight has WEIGHT=101.1 lb.) Notice that in this “**fold913updwn**” case there are many fewer “ALMOST FEASIBLE” data points below WEIGHT=105 lb than exhibited in Fig. A16, and that there is only one “FEASIBLE” data point below WEIGHT=105 lb.

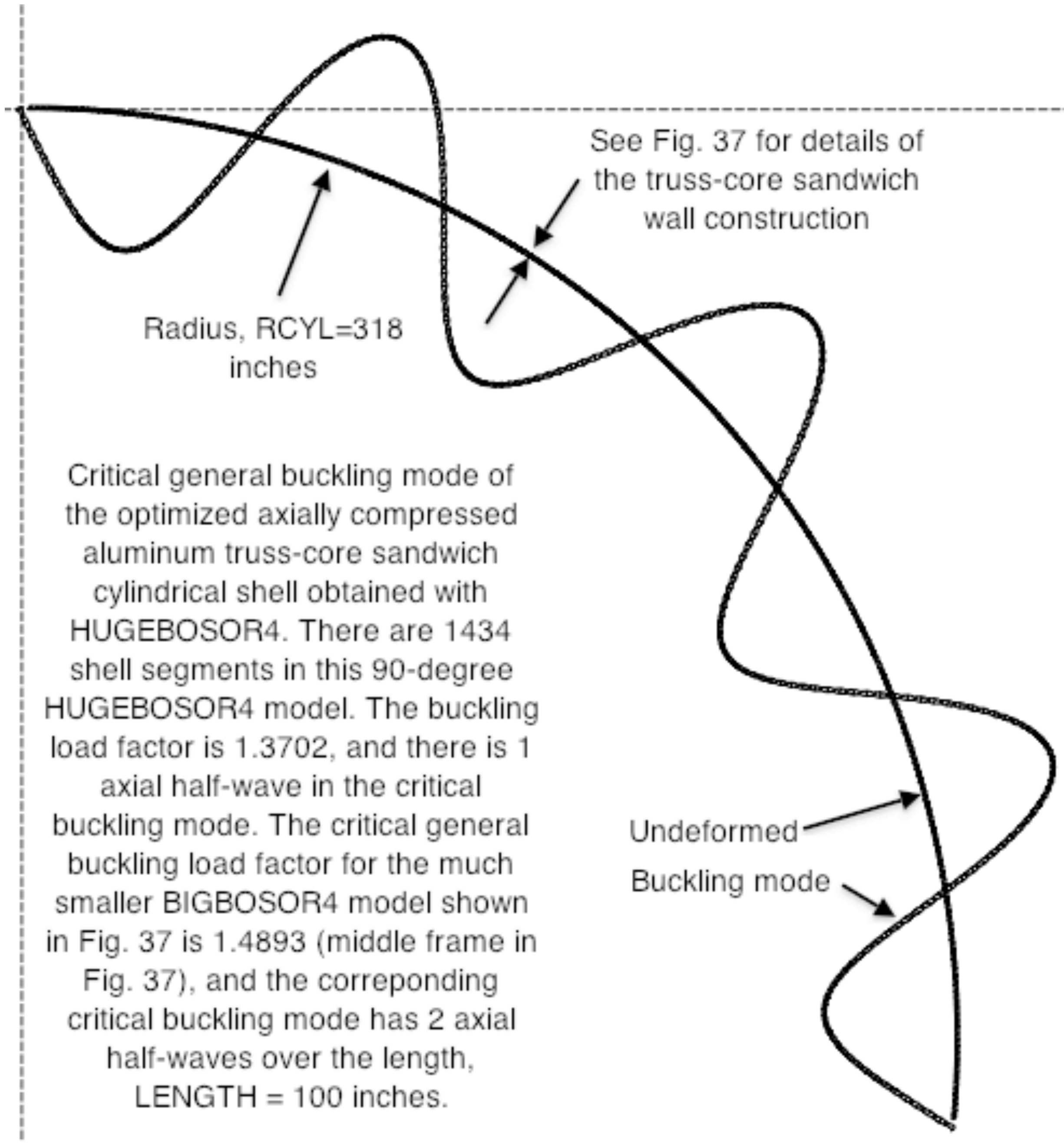


Fig. A19 **A HUGEBOSOR4 model** of 90 degrees of the optimized uniformly axially compressed truss-core sandwich aluminum cylindrical shell "equivalent" to the complexly corrugated cylindrical shell of the type shown in Fig. 33. This "huge" prismatic model includes all the little shell segments, some of which can be seen in the much smaller BIGBOSOR4 model displayed in the top two frames of Fig. 37. The 1434 individual little shell segments cannot be seen in this model because they are too small. This shell was re-optimized with HUGEBOSOR4. The new design: pitch of truss = 1.927 inches; width of truss-core crown = 0.3127 inch; height of truss-core sandwich = 1.142 inch; thickness of truss core sheet = 0.02720 inch; thickness of each face sheet = 0.03495 inch; new weight/area = 0.01158 lb/in^2, very close to the old weight/area = 0.01159 lb/in^2 given in Fig. 37. General and local buckling occur at load factors very close to 1.5 (the specified factor of safety).

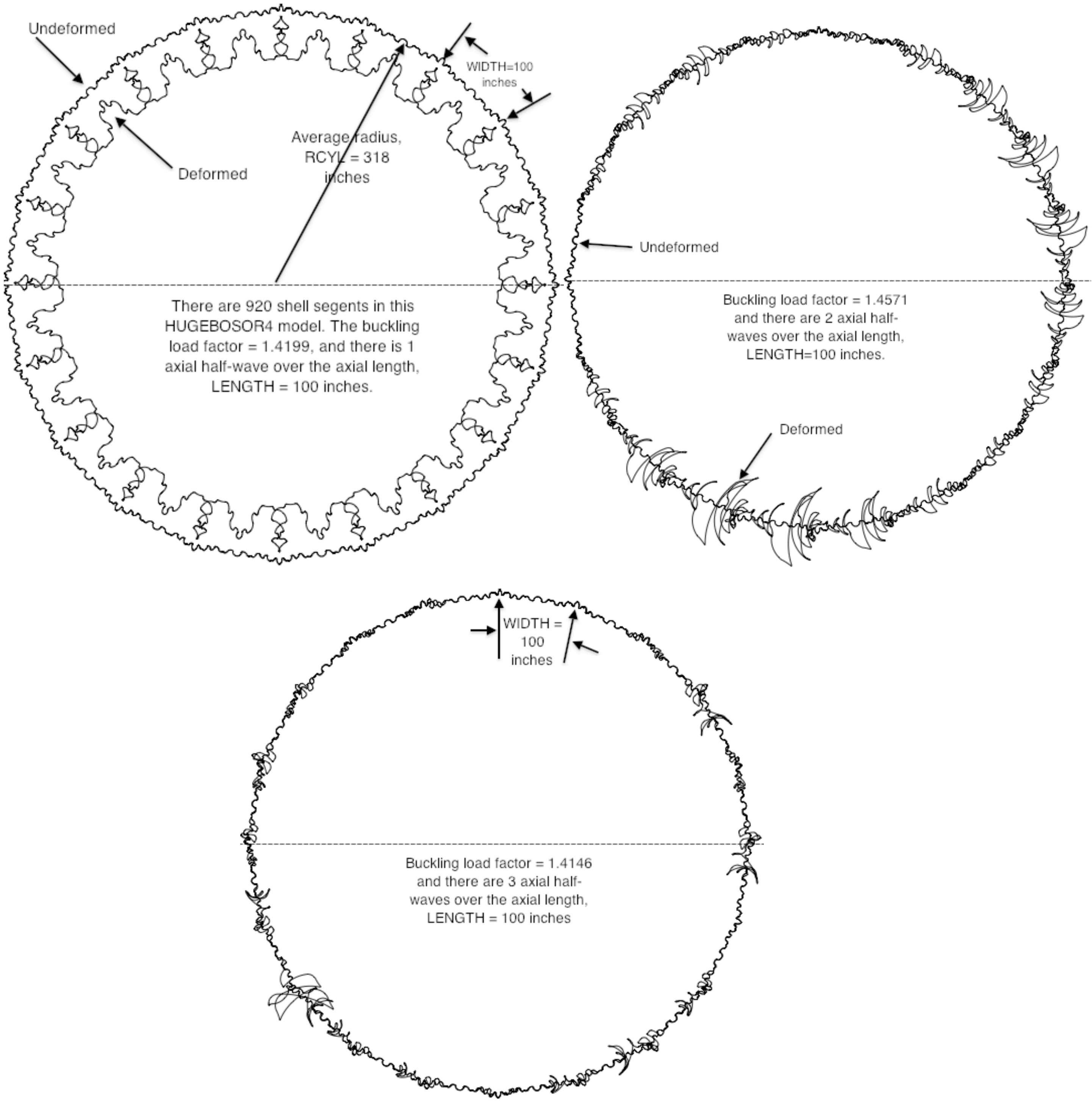


Fig. A20 **Three buckling modes** and load factors from a **HUGEBOSOR4 model** of the optimized specific case called "**fold913updwn**" with "smoothing" present. There are 920 shell segments in this HUGE model. The complex corrugated cross-section profile was first optimized with the use of a much, much smaller BIGBOSOR4 model that includes only WIDTH/2 = 50 inches. (There is a symmetry plane at the mid-width of the small section of width, WIDTH=100 inches.)