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A Probabilistic Method for the Buckling Assessment of Stiffened Composite Shells

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ABSTRACT

A method is described to computationally simulate probabilistic buckling behavior of multi-layered composite shells. The simulation accounts for all naturally-occurring uncertainties including those in constituent (fiber/matrix) material properties, fabrication variables and structure geometry. The method is demonstrated for probabilistically assessing the buckling survivability of a specific case of a stiffened composite cylindrical shell with and without cutouts. The sensitivities of various uncertain variables on the buckling survivability are evaluated at specified reliability. The results show that the buckling survivability for a shell without cutouts depends primarily on shell skin related uncertainties. However, stringer related uncertainties become important for a shell with cutouts.

1. INTRODUCTION

Composite shells are used widely in aerospace structural applications. However, significant scatter has been observed in numerous variables associated with composite materials from which these shells are made and with shell geometry/boundary (attachment or support) conditions. As a consequence, the buckling strength of composite shells is difficult to quantify. In order to account for the various uncertainties and to satisfy the design requirements, knockdown (safety) factors are used extensively. These knockdown factors significantly reduce the design load of composite shells which result in substantial weight increase, but without a quantifiable measure of their reliability.

An alternative design approach which reliably quantifies the buckling strength of composite shells in the presence of uncertainties is probabilistic simulation. The objective of this paper is to describe the probabilistic method and to demonstrate its effectiveness by select composite shell buckling examples.

2. FUNDAMENTAL PROBABILISTIC BUCKLING APPROACH

The proposed approach for the probabilistic assessment of composite shell buckling is based on (1) identifying all possible uncertain variables (called primitive variables), (2) assigning a probabilistic distribution function for each primitive variable, (3) processing all primitive variables through micro-, macro- composite mechanics and laminate theories, finite element methods and probability algorithms, and (4) extracting useful buckling information from the output of the analyzer and checking against probabilistic design criteria.

The uncertain variables in a composite shell structure can come from different composite scales. At the constituent scale, material properties for the fiber and matrix and fiber misalignment are the major sources of uncertainties. At all stages of the fabrication process, the fabrication variables such as fiber volume ratio, void volume ratio, ply misalignment angle and ply thickness show considerable scatter. At the structure scale, the variation of the geometry during the assembly stage, the uncertain boundary conditions and random thermal-mechanical loads, all have significant contribution to the scatter in the composite structural response.

Formal methodology to quantify the scatter in composite structural responses and to assess the composite structural design, progressively propagating all uncertainties including fabrication variables from lower composite scales (constituents) to those at higher composite scales (ply, laminate, structural) was developed as shown in Figure (1). This methodology, integrating micro-, macro-, composite mechanics and laminate theories, finite element methods and probability algorithms, was implemented in the computer code IPACS (Integrated Probabilistic Assessment of Composite Structures) (ref. 1). Since special probability theories (ref. 2) are used instead of the conventional Monte Carlo simulation, tremendous computational efficiency can be gained. Therefore, a probabilistic composite structural analysis becomes feasible which can not be done traditionally, especially for composite shells which have a lot of uncertainty variables.

In the following, the buckling survival probability under applied loads for a cylindrical shell with various cutouts is obtained. Also, sensitivity factors which indicate the relative contribution among the uncertain variables to this probability are determined.

3. DEMONSTRATION FOR PROBABILISTIC ASSESSMENT OF STIFFENED COMPOSITE SHELL BUCKLING

3.1 Composite Shell Geometry, Configuration, Loading, Uncertainties, and Modelling

Thin composite stiffened cylindrical shells without cutouts and with cutouts of various sizes, shown in Figures 2 (a) to (c), are probabilistically assessed for buckling strength. The shell structure consists of a composite skin, five composite horizontal circumferential frames and eight composite vertical stringers. The laminate configurations for skin, frames and stringers are $[\pm 45/0_2/\pm 45/0_2/\pm 45/0/90]_s$, $[0_{24}]$ and $[0_{24}]$ respectively. The shell is free at the top end and its bottom end support is modeled by a set of translational and torsional spring constants. The shell is subjected to axial, lateral and torsional loads at its free end as also shown in Figures 2.

The shell skin, horizontal frames, and vertical stringers are modelled by 1258 nodes (6 dof per node) and 1208 four-noded shell elements. The primitive variables include material properties for graphite fiber and material properties for the epoxy matrix of skin, frames and stringers at the constituent scale. The fabrication variables include the fiber volume ratio, the void volume ratio, the ply orientation, and the ply thickness. At structural scale, support spring constants are assigned a probability distribution to reflect the real-life attachments and the circumferential frame spacing are also assumed to be uncertain to reflect the uncertainty from the manufacturing process. Their respective probability distribution type and associated parameters (mean and scatter) are listed in Table 1.

3.2 Composite Shell Probabilistic Buckling Results

Three cases of cylindrical shell, namely, (a) without cutout, (b) with uniform cutouts and (c) with uniform cutouts and an access port, as shown in Figure (2), are assessed for their respective probability of buckling survivability under applied load.

3.2.1 Cylindrical shell without cutouts

Figures (3a) to (3c) show the mean buckling mode shapes for the first three buckling modes of the shell without cutouts. All three modes are the combination of skin and stringer buckling as indicated. Figure (3d) shows the buckling survival probability under applied loads. For a given applied load, for example, the reference load, the reliability against buckling for the first three buckling modes can be readily found from this figure as 0.85, 0.96 and 0.99 respectively. The sensitivity factors at the 0.999 reliability level shown in Figures (4a) to (4c) indicate that the sensitivity factors (ref. 2) for the fiber modulus, the fiber volume ratio and the laminate thickness of the skin are significantly higher than those for stringers. This type of information is useful for the design decision making process. For example, if the design reliability against buckling instability is not acceptable, a redesign is required. From the sensitivity analysis, it is found that the reliability can be improved much more by enhancing the quality of the skin related uncertainties rather than enhancing the quality of the stringer related uncertainties.

3.2.2 Cylindrical shell with uniform cutouts

The first three buckling mode shapes are shown in Figures (5a) to (5c). In this case, the skin is buckled around the cutouts while the entire skin buckled in the case without cutouts. Also, for the same applied load, the buckling survival probability is significantly lower for the shell with uniform cutouts (Figure (5d)) than that for shell without cutouts (Figure (3d)). The sensitivity results in Figures (6a) to (6c) show that in the presence of uniform cutouts, the buckling survivability is sensitive to both the skin and stringer related variables.

3.2.3 Cylindrical shell with uniform cutouts and an access port

The access port is a cutout between the circumferential frames and vertical stringers. Therefore, one of the local skin buckling modes in the previous case is eliminated. The mean buckling mode shapes are shown in Figures (7a) to (7c). Similar to the case for uniform cutouts only, the skin is buckled around the uniform cutouts. It is noticed that the buckling survival probability under applied loads for the first mode (Figure (7d)) increases compared with that for the case with uniform cutouts only (Figure (5d)) because part of the local skin instability is eliminated. However, due to this access port, more load is taken by the stringers which results in an early buckling and the reduction of the buckling survival probability for second and third mode. The sensitivity factors (in Figure (8a) to (8c)) show that the contribution to the failure probability by the stringer related uncertainties can not be ignored.

4. CONCLUSIONS

A formal methodology is described for the probabilistic assessment of buckling of composite shells. This methodology integrates micro and macro composite mechanics, laminate theory, structural mechanics (finite element methods), and probability algorithms to perform a probabilistic assessment of composite structural design accounting for uncertainties in all requisite variables at all composite scales. Buckling of a typical composite shell with various cutouts was assessed probabilistically. For the demonstration case studied herein, it is found that the skin-related uncertain variables dominate the buckling survival probability under applied loads for the shell without cutouts. The stringer-related uncertain variables become important in the presence of cutouts. The access port, bounded by stringers, shows higher survival probability under applied loads than the shell with uniform cutouts which are not bounded by stringers.

5. REFERENCES

1. C. C. Chamis, M. C. Shiao, "IPACS -- Integrated Probabilistic Assessment of Composite Structures: Code Development and Applications", Third NASA Advanced Composite Technology Conference, 1992.

2. Y. T. Wu, "Demonstration of a New, Fast Probability Integration Method for Reliability Analysis", Advances in Aerospace Structural Analysis, O. H. Burnside and C. H. Parr, ed., ASME, New York, pp.63-73, 1985.

6. SYMBOLS

E_{f11} : fiber modulus in longitudinal direction
E_{f22} : fiber modulus in transverse direction
G_{f12} : in-plane fiber shear modulus
G_{f23} : out-of-plane fiber shear modulus
ν_{f12} : in-plane fiber Poisson's ratio
ν_{f23} : out-of-plane fiber Poisson's ratio
E_m : matrix elastic modulus
G_m : matrix shear modulus
ν_m : matrix Poisson's ratio

FVR : fiber volume ratio

stdv : standard deviation

COV : Coefficient Of Variation

Table 1. Statistics for Uncertainties

	Uncertain Variables	Distribution Type	Mean	COV (%Mean)
fiber properties	E_{f11} (Msi)	Normal	31.0	5
	E_{f22} (Msi)	Normal	2.0	5
	G_{f12} (Msi)	Normal	2.0	5
	G_{f23} (Msi)	Normal	1.0	5
	ν_{f12}	Normal	0.2	5
	ν_{f23}	Normal	0.25	5
matrix properties	E_m (Msi)	Normal	0.5	5
	G_m (Msi)	Normal	0.185	5
	ν_m	Normal	0.35	5
fabrication variables	fiber volume ratio	Normal	0.60	5
	void volume ratio	Normal	0.02	5
	ply misorientation (degree)	Normal	0.00	0.9 (stdv)
	skin ply thickness (in)	Normal	0.005	5
	stringer ply thickness (in)	Normal	0.02	5
structural variables	frame spacing (in)	Normal	150.0	2

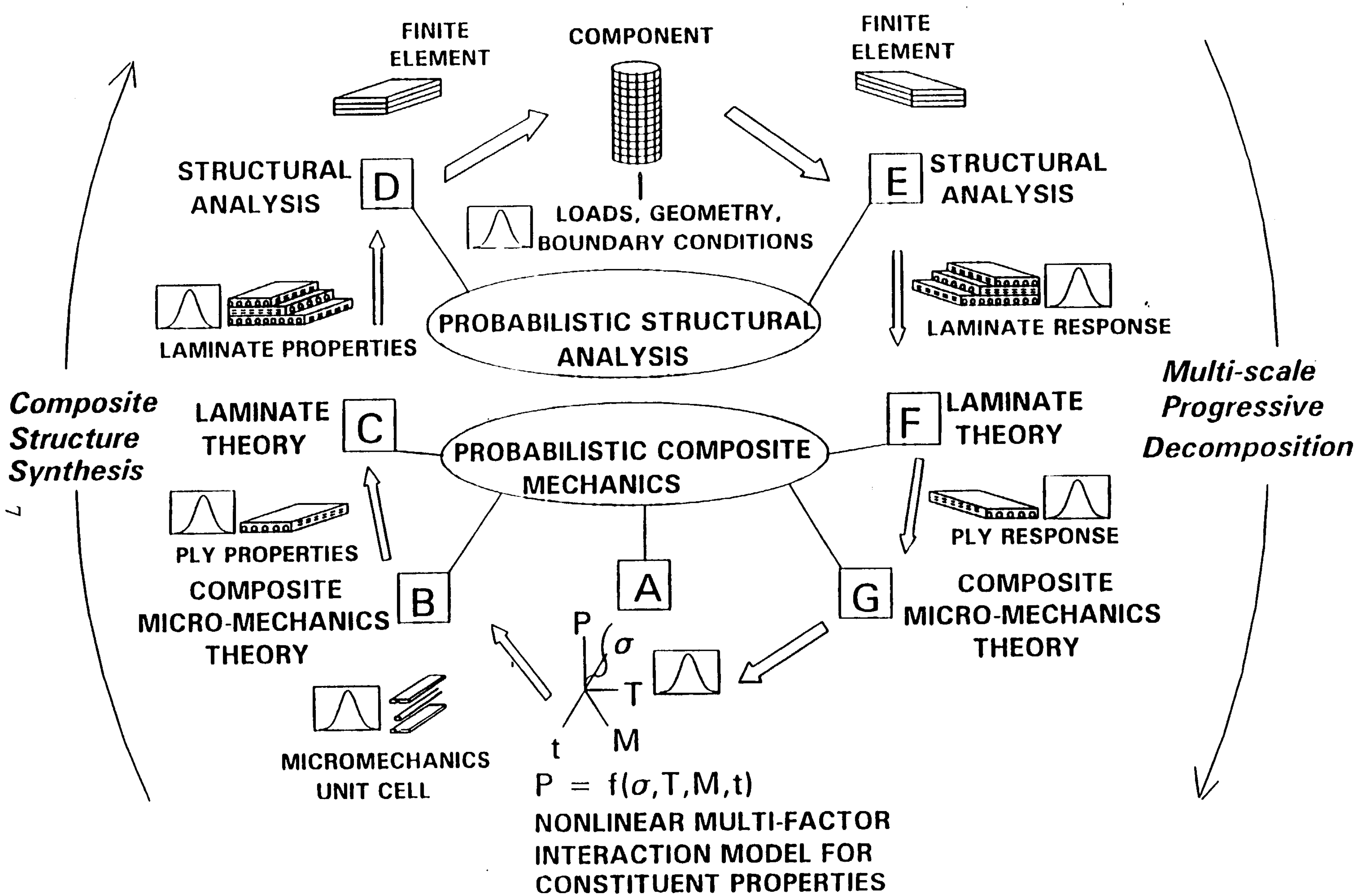
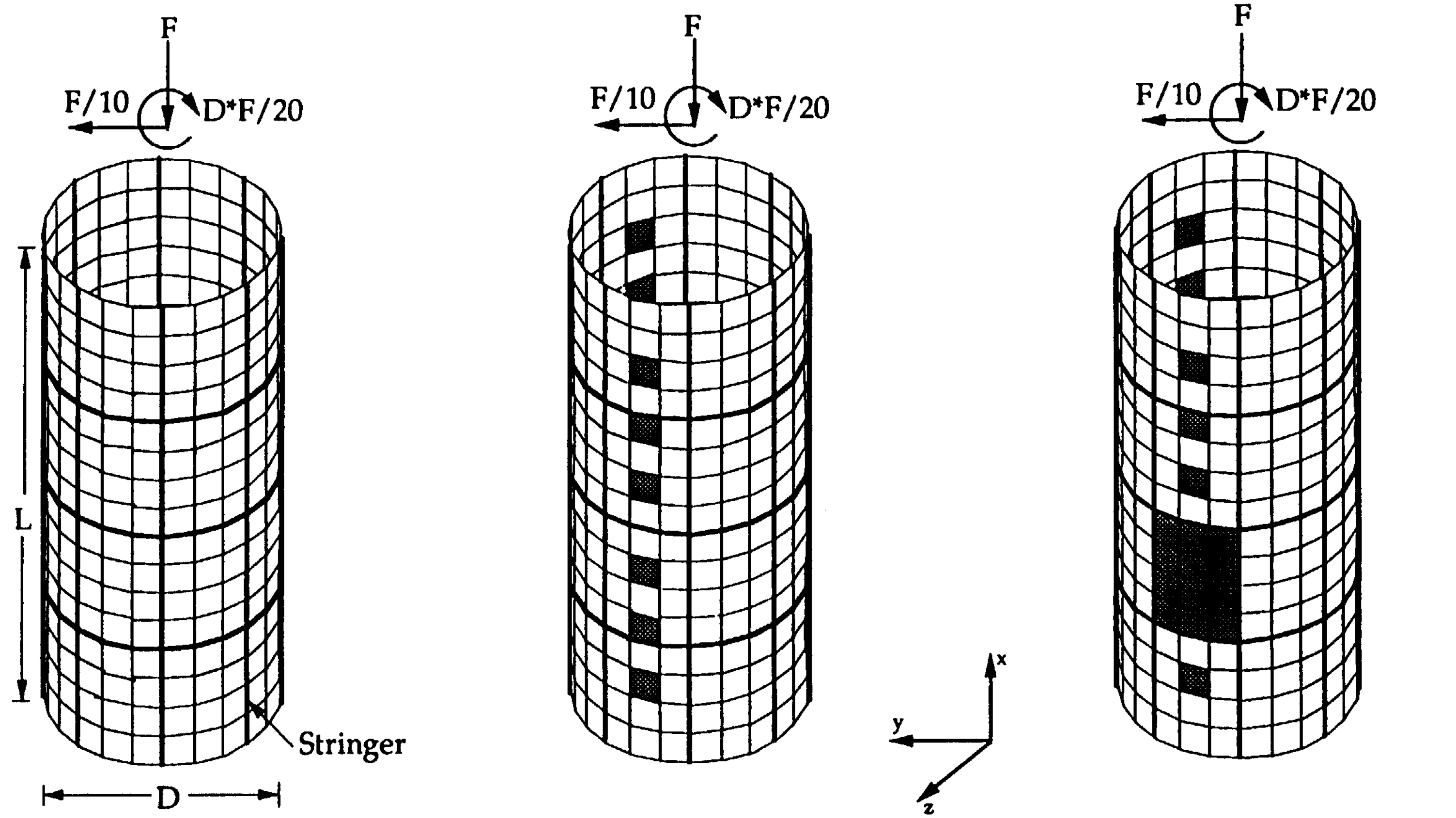


Figure 1. Probabilistic Assessment of Composite Structures



(a) Without Cutouts

(b) With Uniform Cutouts Largest Hole = 1 Unit Cutout

(c) With an Access Port Largest Hole = 12 Unit Cutouts

D = Diameter , L = Length , F = Axial Force, L/D=2.5

Size of the Unit Cutout = (L/16) * (πL/60)

Figure 2. Stiffened Composite Cylindrical Shell with Various Cutouts

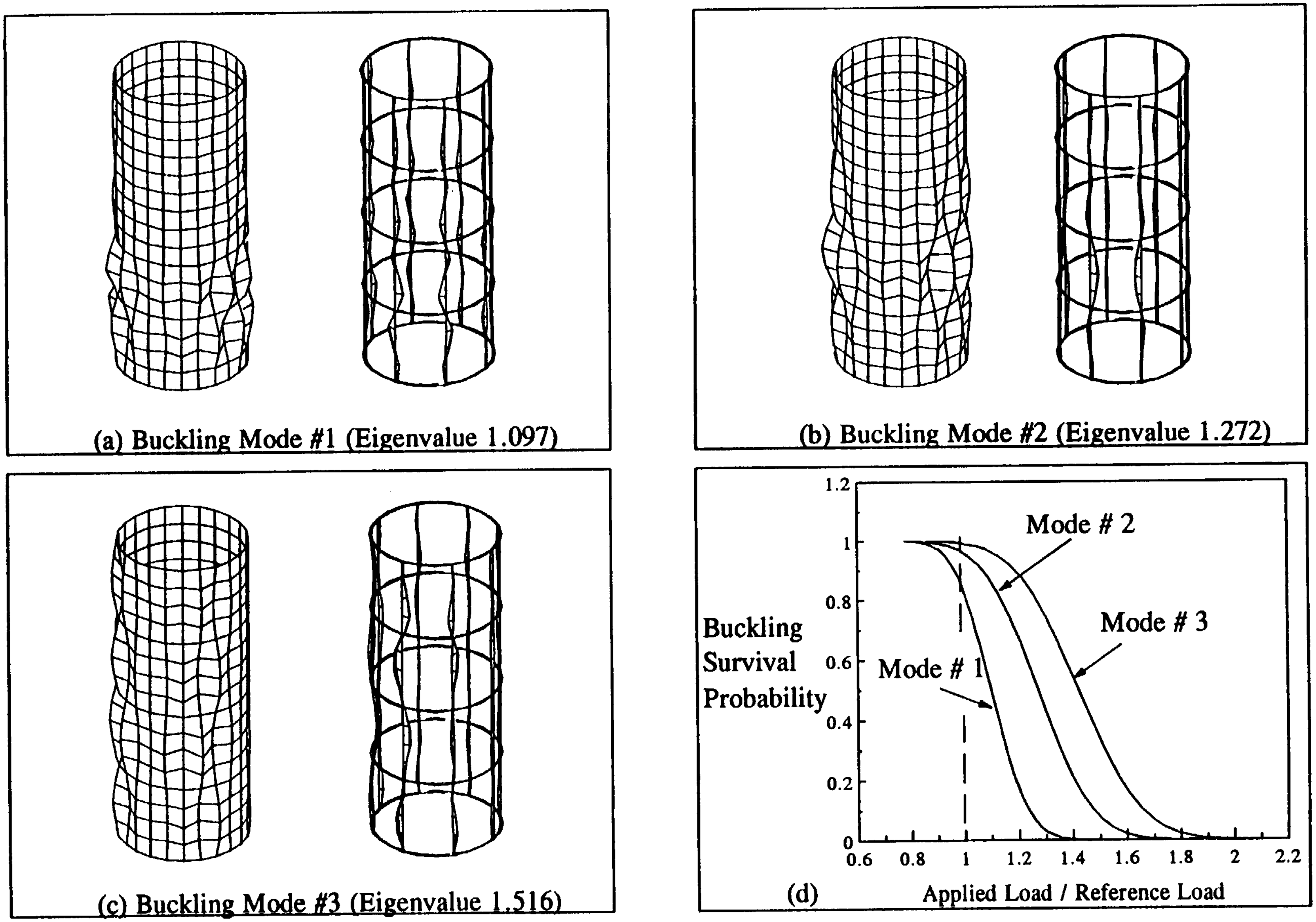


Figure 3. Buckling Mode Shapes and Buckling Survival Probability (Cylindrical Shell without Cutouts)

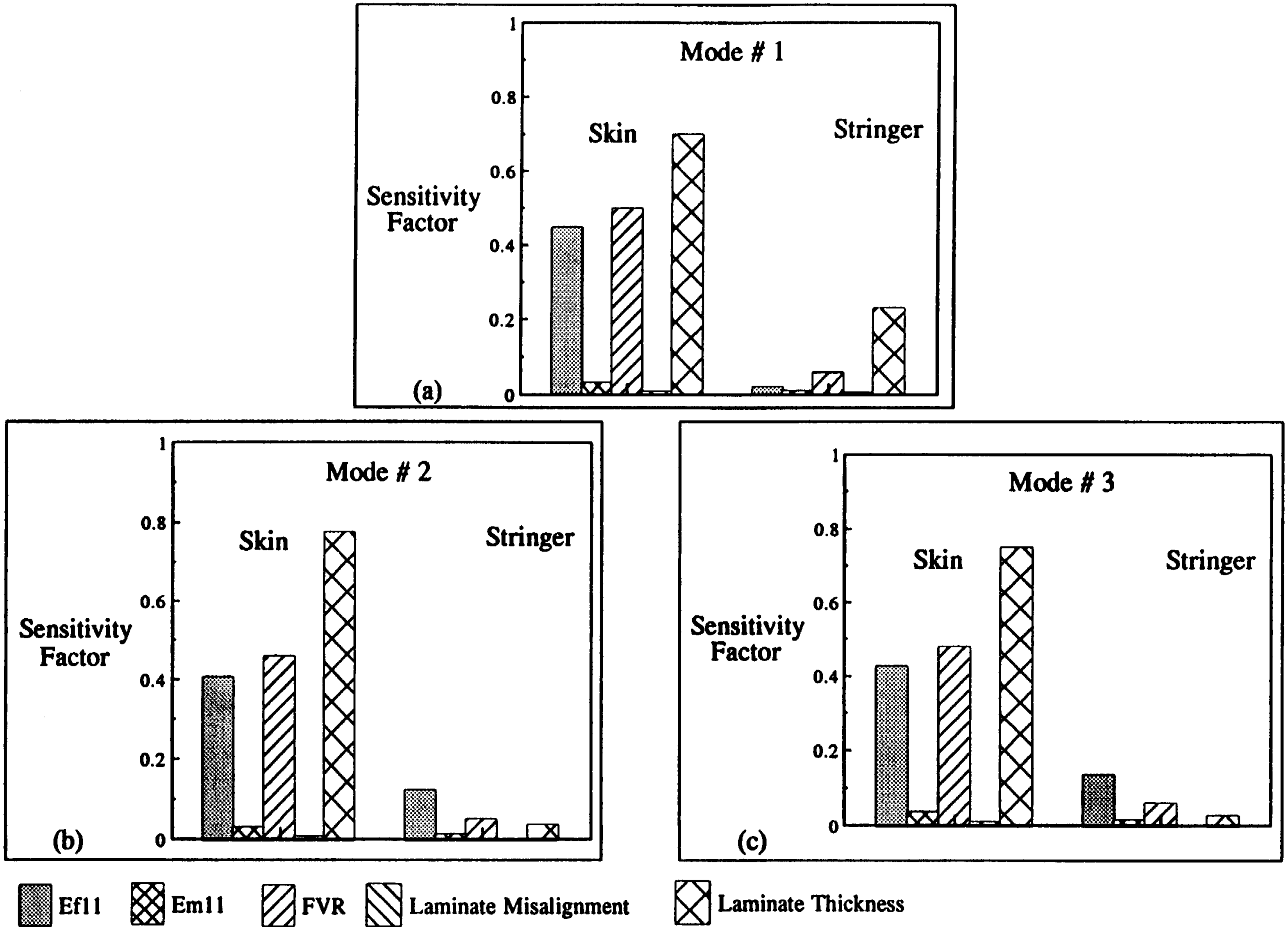
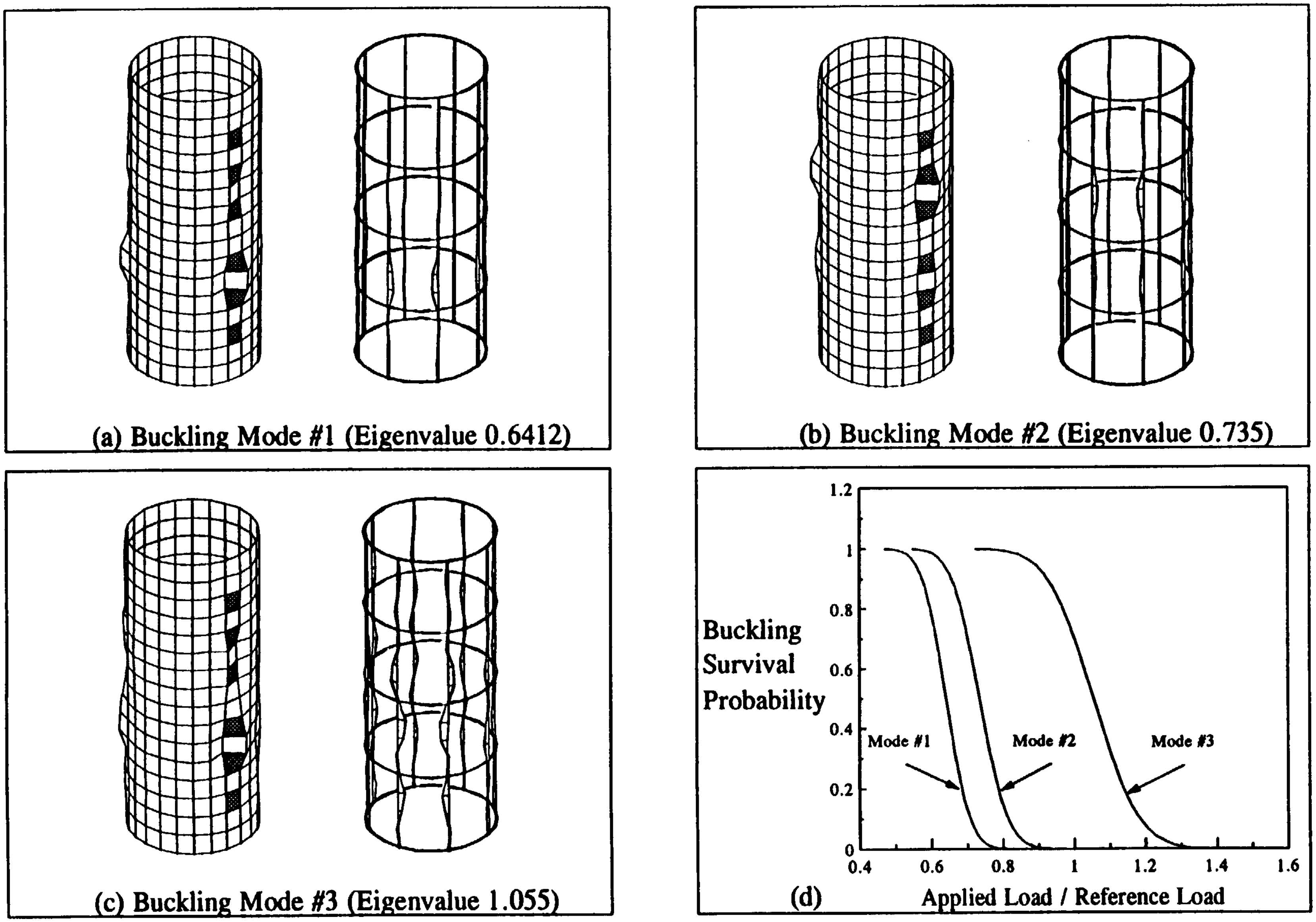


Figure 4. Sensitivity Factors at 0.999 Buckling Survival Probability (Cylindrical Shell without Cutouts)



(a) Buckling Mode #1 (Eigenvalue 0.6412)

(b) Buckling Mode #2 (Eigenvalue 0.735)

(c) Buckling Mode #3 (Eigenvalue 1.055)

(d)

Figure 5. Buckling Mode Shapes and Buckling Survival Probability (Cylindrical Shell with Uniform Cutouts)

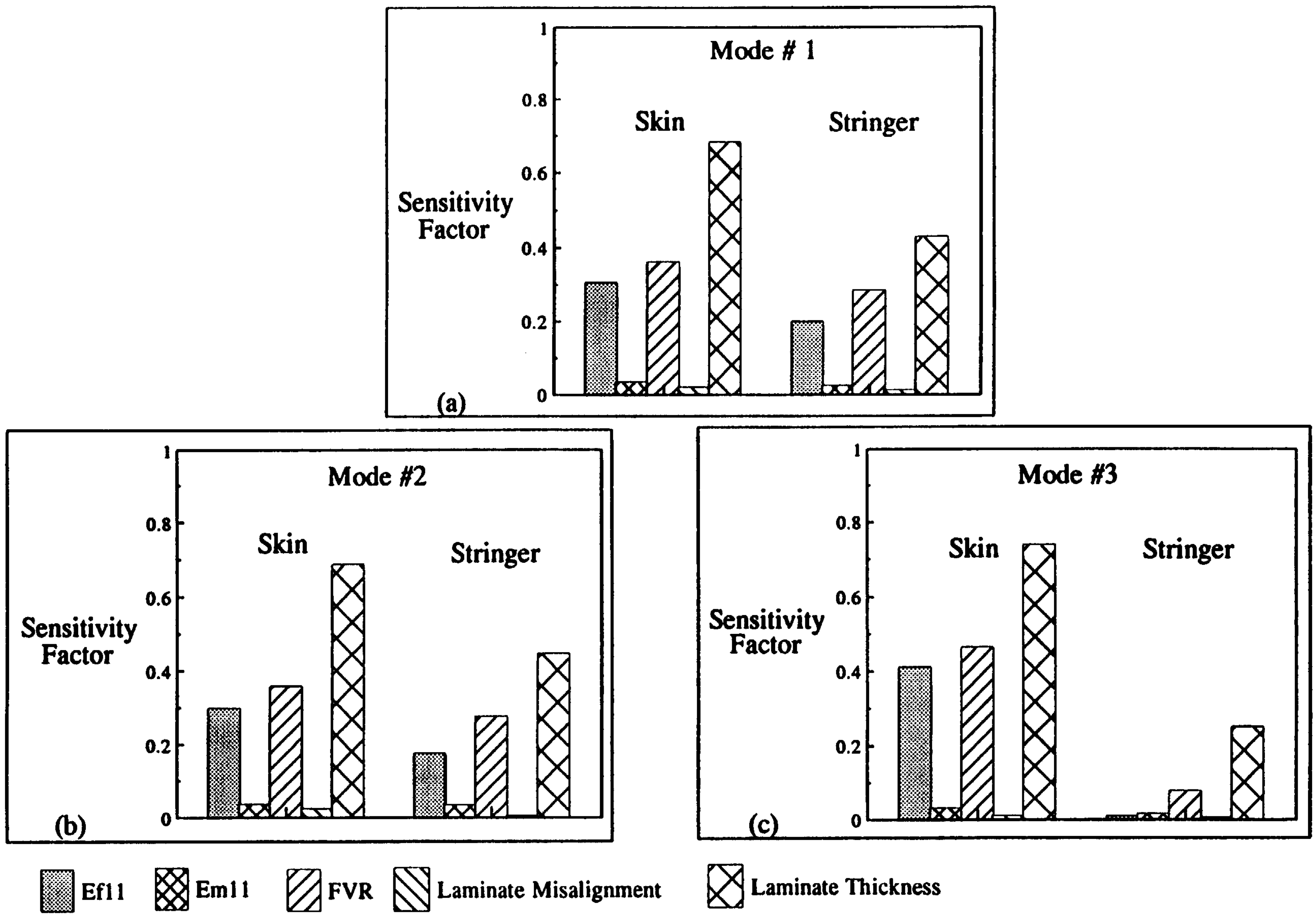


Figure 6. Sensitivity Factors at 0.999 Buckling Survival Probability (Cylindrical Shell with Uniform Cutouts)

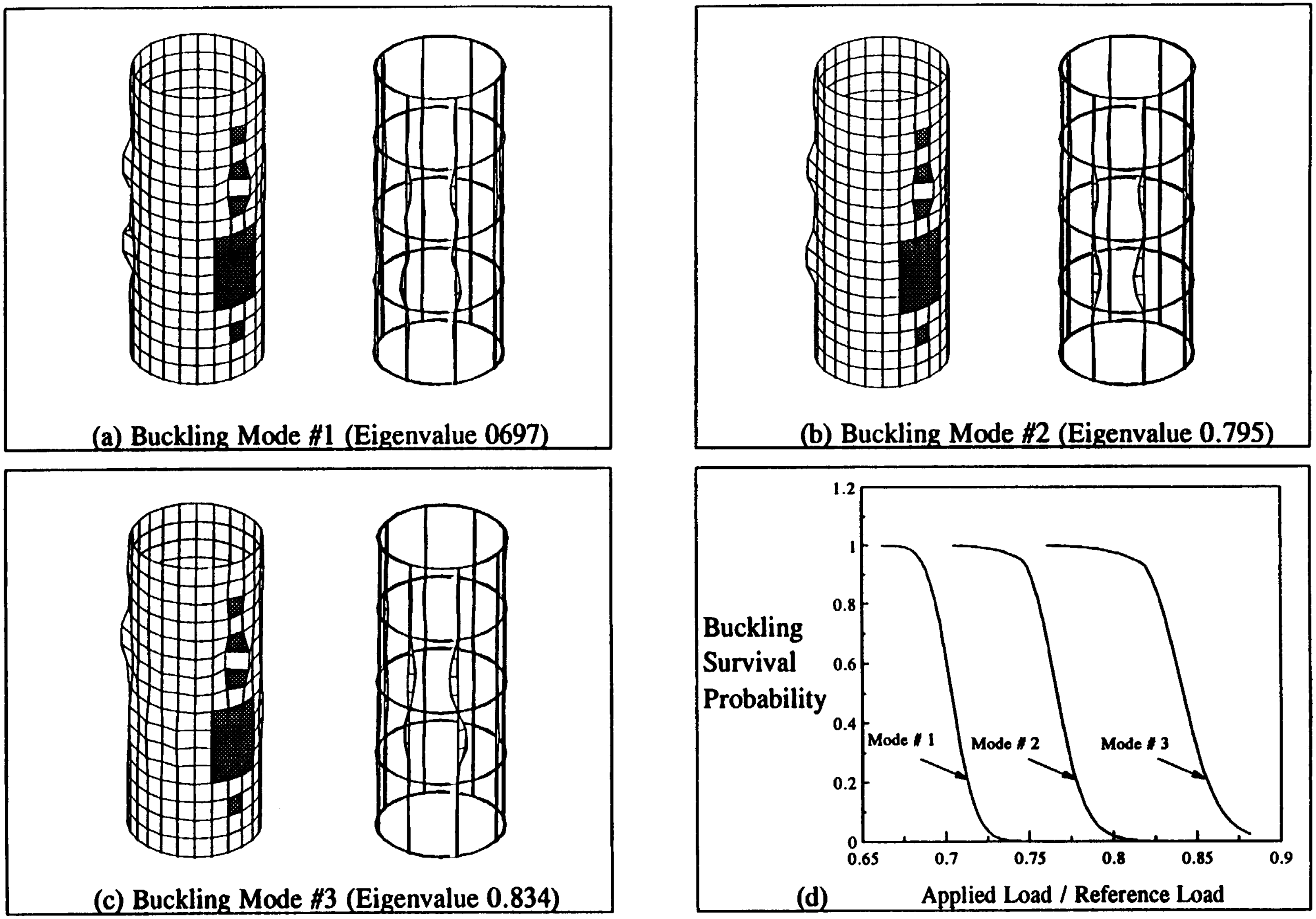


Figure 7. Buckling Mode Shapes and Buckling Survival Probability (Cylindrical Shell with an Access Port)

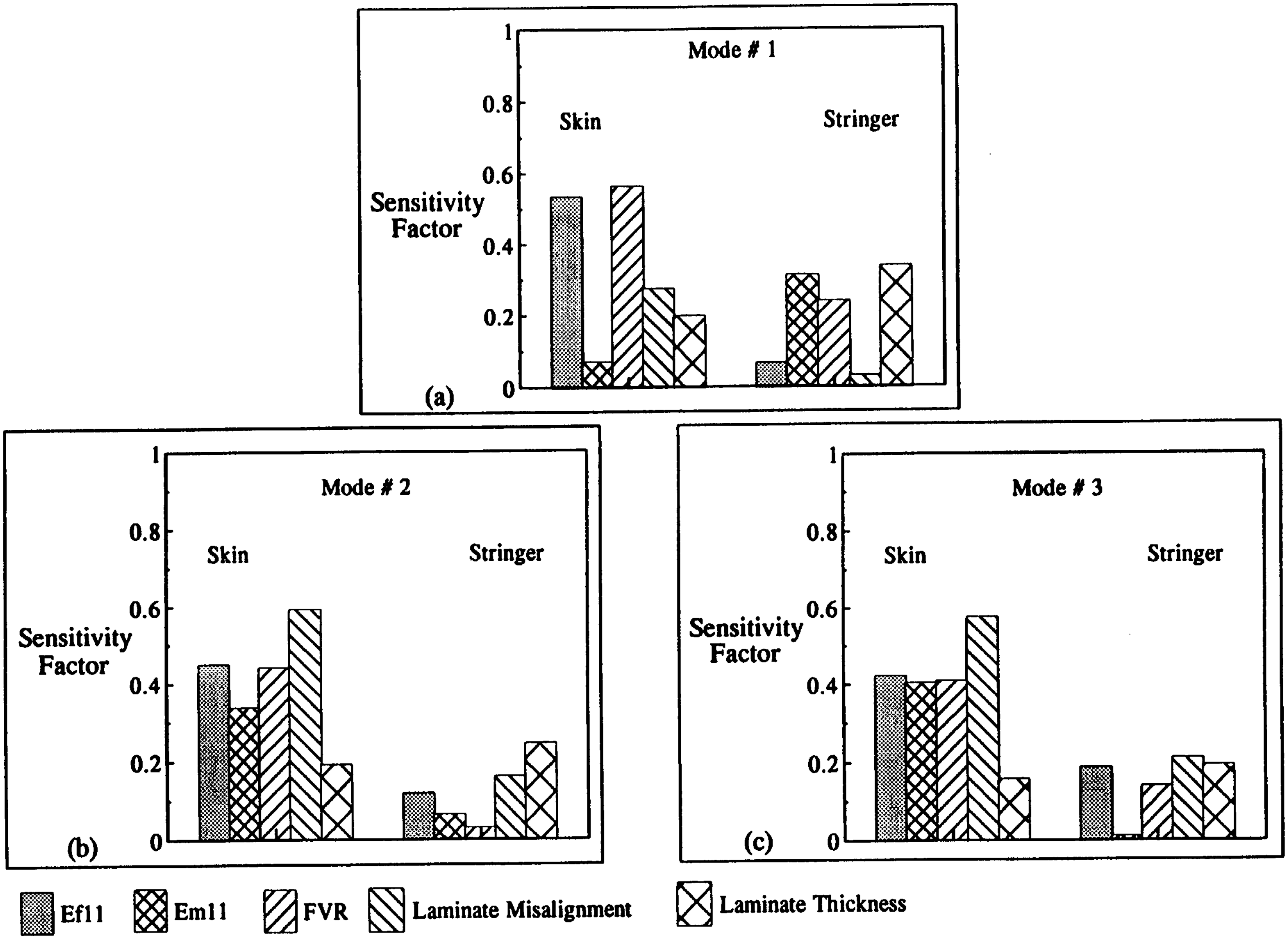


Figure 8. Sensitivity Factors at 0.999 Buckling Survival Probability (Cylindrical Shell with an Access Port)

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13. ABSTRACT *(Maximum 200 words)*

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