Quantification of Building Seismic Performance Factors Component Equivalency Methodology - FEMA P-795

Charles A. Kircher, Ph.D., P.E.
Principal
Kircher & Associates, Consulting Engineers
Palo Alto, CA

Curt B. Haselton, Ph.D., P.E.
Chair and Associate Professor
Department of Civil and Environmental Engineering
California State University, Chico, CA

Abbie B. Liel, Ph.D., P.E.
Assistant Professor
Civil, Environmental and Architectural Engineering
University of Colorado, Boulder, CO

Introduction

This paper describes the recommended methodology of FEMA P-795 (FEMA 2011) for evaluating the seismic performance equivalency of structural elements, connections, or subassemblies whose inelastic response controls the collapse performance of a seismic-force-resisting system. The recommended Component Equivalency Methodology (referred to as the Component Methodology) is a statistically-based procedure for developing, evaluating and comparing test data on new components (*proposed components*) that are proposed as substitutes for selected components (*reference components*) in a current code-approved seismic-force-resisting system (*reference SFRS*).

The Component Methodology is derived from the general methodology contained in FEMA P-695 *Quantification of Building Seismic Performance Factors* (FEMA 2009). Like the general methodology in FEMA P-695, the intent of the Component Methodology is to ensure that code-designed buildings have adequate resistance against earthquake-induced collapse. In the case of component equivalency, this intent implies equivalent safety against collapse when proposed components are substituted for reference components in the reference SFRS.

Proposed components found to be equivalent by the Component Methodology can be substituted for components of the reference SFRS, subject to design requirements and seismic design category restrictions on the use of the reference SFRS. Reference SFRSs include the seismic-force-resisting-systems contained in ASCE/SEI 7-10 *Minimum Design Loads for Buildings and Other Structures* (ASCE, 2010).[1]

This paper begins with an overview of the ATC 63-1 Project that developed the Component Methodology of FEMA P-795 including sections on background and purpose, objectives and scope, assumptions and limitations, anticipated use and implementation, and the technical approach of the methodology. The paper then demonstrates an example application of the Component Methodology using the results of a "beta test" study (i.e., Appendix F of FEMA P-795) that evaluated the equivalency of a pre-fabricated wall component proposed for substitution in light-frame wood construction.

---

[1] For use in this Component Methodology, the term "component" refers exclusively to structural elements, connections, etc. In contrast, the term "component" in ASCE/SEI 7-10 refers exclusively to nonstructural components.

Background and Purpose

The Applied Technology Council (ATC) was commissioned by the Federal Emergency Management Agency (FEMA) under the ATC-63 Project to develop a methodology for quantitatively determining the response modification factor (R factor), the system overstrength factor (Ω_O), and the deflection amplification factor (C_d) used in prescriptive seismic design procedures found in modern building codes. Collectively referred to as "seismic performance factors," these factors are fundamentally critical in the specification of seismic design loading. They are used to estimate strength and deformation demands on seismic-force-resisting systems that are designed using linear methods of analysis, but are responding in the nonlinear range.

The final report of the ATC-63 Project, FEMA P-695 (FEMA, 2009), outlines a procedural methodology for quantifying collapse behavior and establishing seismic performance factors for newly proposed structural systems. The FEMA P-695 Methodology relies on collapse simulation through nonlinear response history analysis of structural systems. It accounts for potential uncertainties in ground motions, component design parameters, structural configuration, and behavioral characteristics of structural elements based on available laboratory test data. It is anticipated that this methodology will be used by the nation's seismic code development committees to set minimum acceptable design criteria for code-approved systems, and to provide guidance in the selection of appropriate design criteria for newly proposed structural systems that are designed using linear design methods.

While complete systems are often proposed for adoption as new seismic-force-resisting systems, it is also common that new structural components, connections, or subassemblies are proposed for use in current code-approved seismic-force-resisting systems. Such components are usually evaluated on the basis that the new component, when substituted for components of the reference system, would result in equivalent (or better) seismic performance.

Although the general FEMA P-695 Methodology could be used to evaluate the seismic performance capability of new components, FEMA initiated the follow-on ATC 63-1 Project, to simplify and adapt the general methodology contained in FEMA P-695 for use in evaluating the specific case of component equivalency. While the general FEMA P-695 Methodology is based on both experimental testing and nonlinear dynamic analyses of archetypical structures, the Component Methodology is based primarily on experimental testing of components.

The resulting Component Methodology described in this paper is not intended to replace the FEMA P-695 Methodology for the evaluation of new systems, but is intended to provide an additional tool for evaluating equivalency of components meeting certain applicability criteria.

Objectives and Scope

The Component Methodology measures equivalency of proposed and reference components by comparing key performance parameters, including deformation capacity, strength, stiffness, and effective ductility capacity. Values of these key parameters are determined from statistical evaluation of test data. The Component Methodology is based on the following two basic performance objectives:

- The proposed components can replace the reference components in the reference SFRS without adversely affecting the seismic performance of the reference SFRS.

- The collapse performance of the reference SFRS complies (or is assumed to comply) with the collapse objectives of the FEMA P-695 Methodology.

The first objective is used to establish the quantitative acceptance criteria in the Component Methodology. The second objective is more qualitative in nature, recognizing that many existing seismic-force-resisting systems of ASCE/SEI 7-10 have not been comprehensively evaluated using the FEMA P-695 Methodology. Limited evaluation of selected seismic-force-resisting systems has shown that these systems generally comply with the collapse objectives of the FEMA P-695 Methodology (FEMA 2009 and NIST 2010). Therefore, provided that the currently approved seismic-force-resisting systems in ASCE/SEI 7-10 have well established design criteria and supporting test data, they are permitted to be used as a reference SFRS in the Component Methodology.

The scope of the Component Methodology is limited to proposed components that meet certain applicability criteria. These criteria determine the suitability of the seismic-force-resisting system for which the component is proposed (the reference SFRS), define minimum quality requirements for design and testing data, and establish limits on the use of the procedures in terms of performance-related attributes. The Component Methodology applies to components that have well defined boundaries within the reference SFRS, and where the seismic performance of the reference SFRS is not otherwise altered by the replacement of reference components with proposed components. While the scope of the Component Methodology is intended for broad application, it may not be applicable to all types of proposed components. Where the Component Methodology does not apply, the more general procedures of the FEMA P-695 Methodology should be used to evaluate component equivalency.

The Component Methodology envisions that proposed components can be used to replace some or all reference components within a reference SFRS. While partial replacement (i.e., "mixing") of proposed and reference

components within a system is desirable for design versatility, it could inadvertently create a vertical or horizontal irregularity in the seismic-force-resisting system if the proposed and reference components do not have sufficiently similar strength and stiffness. Subject to certain restrictions, the Component Methodology permits partial replacement of components by limiting differences in the strength and stiffness of proposed and reference components.

Assumptions and Limitations

The Component Methodology is intended to apply to a broad range of component types proposed for use in any of the existing seismic-force-resisting systems of ASCE/SEI 7-10, subject to certain applicability criteria. Practical application of the Component Methodology, however, will likely be limited to those components for which there is sufficient quality and quantity of test data for judging equivalency. This section summarizes key assumptions and potential limitations of the Component Methodology with respect to the equivalency approach and applications.

Equivalency Approach

The Component Methodology is based on the concept of component equivalency as a practical means of achieving an acceptable level of collapse safety for the seismic-force-resisting system of interest. The equivalency approach necessarily assumes that collapse safety of the reference SFRS is adequate before proposed components are substituted for reference components, and the acceptance criteria of the Component Methodology ensure that collapse safety will remain adequate when the proposed substitutions are made. Applicability criteria limit application of the Component Methodology to proposed component types that are considered suitable for evaluation using an equivalency approach, and to currently approved systems that are considered suitable for use as a reference SFRS.

Suitability of the Reference Seismic-Force-Resisting System

In the FEMA P-695 Methodology, adequacy of collapse resistance is evaluated in an absolute sense using criteria that define an acceptable probability of collapse for maximum considered earthquake (MCE_R) ground motions. In the Component Methodology, adequacy of collapse resistance is evaluated in a relative sense using criteria that compare proposed and reference component performance, assuming that the reference SFRS complies with the collapse performance criteria of FEMA P-695.

Ideally, only those existing systems with adequate collapse safety would be used as a reference SFRS. For pragmatic reasons, however, the Component Methodology permits existing systems of ASCE/SEI 7-10 to be used as the reference system without being shown to comply. First, it would not be practical for the Component Methodology to require

implementation of FEMA P-695 Methodology to evaluate the reference SFRS before evaluating component equivalency. Second, example evaluations of a number of current code-approved systems have shown that, in general, they substantially comply with FEMA P-695, except for very short-period building configurations (FEMA 2009 and NIST 2010).

Short-period configurations tend to have reduced resistance to collapse, regardless of the type of force resisting system, reflecting a generic shortcoming of current code design requirements. Generic shortcomings of current code design requirements, while unfortunate, are not considered sufficient by themselves to render the ASCE/SEI 7-10 system of interest unsuitable for use as a reference SFRS.

Suitability of Proposed Components

While the Component Methodology is intended to apply broadly to many different types of components, equivalency concepts may not be applicable or appropriate in all cases. Figure 1 illustrates, conceptually, two fundamental issues regarding the applicability of the Component Methodology. The first is whether or not the proposed product is a new "system" or a new "component." The second is whether or not the new component has characteristics (and appropriate data) suitable for evaluation using equivalency methods.
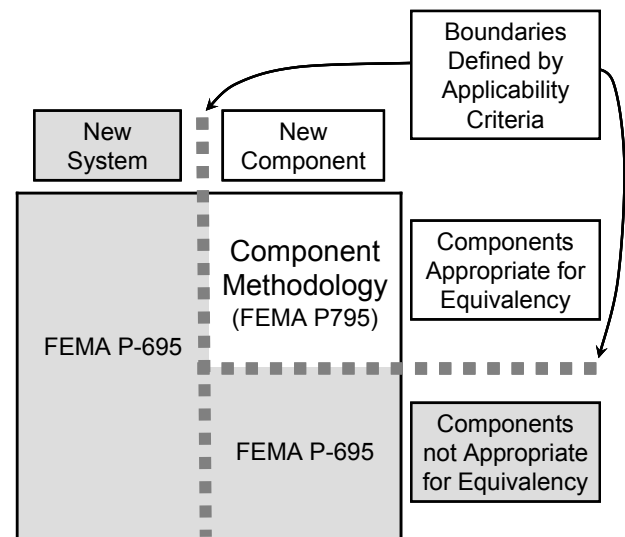

Figure 1. Conceptual boundaries defined by applicability criteria of the Component Methodology.

The boundaries shown in Figure 1 are defined by a detailed set of applicability criteria. It is possible that some new products will not meet these criteria. In such cases, FEMA P-695 provides the methodology that should be used for evaluation of new products that are deemed inappropriate for evaluation by the Component Methodology.

<u>Test Data and Design Requirements Limitations</u>

The Component Methodology requires a minimum quality and quantity of component test data, and a minimum quality of component design information. Lack of availability of these data, in particular reference component test data, could limit use of the Component Methodology for some reference SFRSs.

Proposed component test data are expected to be developed as part of product development. While the Component Methodology requires somewhat more extensive cyclic-load (and monotonic-load) testing than is typically used to support product development and approval, such testing is within the control of the proponent. Reference component test data are expected to be obtained from existing sources, such as previous tests of components of the reference system of interest. Unfortunately, sources of reference component test data can be limited. While it is possible for product developers to conduct the necessary tests of reference components, such testing may not be practical.

While results of laboratory tests of structural elements of different material types appear frequently and extensively in a number of technical publications, few research programs have comprehensively investigated any given system of ASCE/SEI 7-10. The vast majority of the approximate 80 systems in Table 12.2-1 of ASCE/SEI 7-10 do not have sufficient quality (or quantity) of data required for equivalency evaluation. Of the relatively small number systems with requisite test data, only a few (such as light-frame wood structural panels) have readily useable databases of test results. Lack of readily useable, quality reference component "benchmark" data is likely the most significant limitation on the use of the Component Methodology.

Anticipated Use and Implementation

The Component Methodology is intended as a technical resource for use by seismic codes and standards development committees, product evaluation services, and product manufacturers, suppliers and their consultants.

While the Component Methodology of FEMA P-795 is based on and related to the FEMA P-695 Methodology, they are fundamentally different in their applications. FEMA P-695 is intended primarily for use in the development of seismic performance factors for a new seismic force resisting system, for which seismic codes and standards committees are ultimately responsible for adoption; whereas, FEMA P-795 is intended primarily for use in establishing the equivalency of a new component, for which product evaluation services have traditionally been responsible for issuing evaluation reports.

While seismic code and standards committees may choose to reference FEMA P-795 (e.g., in code commentary), or possibly adopt applicable portions of the methodology (with

modification), or even develop a new standard based on methodology, product evaluation services such as the International Code Council Evaluation Services (ICC ES), are the most likely immediate users of FEMA P-795. In this case, the Component Methodology provides ICC-ES with a technically sound basis for establishing product evaluation report acceptance criteria.

Precisely how the Component Methodology of FEMA P-795 will be implemented by potential users is not known at this time and is ultimately the responsibility of the interested organizations. As part of on-going work by the Provisions Update Committee (PUC) of Building Seismic Safety Council (BSSC) to develop the 2014 edition of the *NEHRP Recommended Seismic Provisions for New Buildings and Other Structures*, a special Issue Team has been formed to study implementation of FEMA P-695 and FEMA P-795 methodologies. This Issue Team will address if, and in what manner, the PUC should make use of the Component Methodology of FEMA P-795.

Technical Approach

The development of the Component Methodology necessarily balanced two competing objectives: (1) maintaining consistency with the probabilistic, analytical, system-based, collapse assessment concepts of the FEMA P-695 Methodology; and (2) providing simple procedures for comparing the tested performance of different components. Work involved the following tasks designed to systematically investigate the trade-offs between these objectives:

- Identification of Key Component Performance Parameters

- Development of Component Testing Requirements

- Development of Probabilistic Acceptance Criteria

<u>Identification of Key Component Performance Parameters</u>

Key component performance parameters were identified through literature review and numerical collapse sensitivity studies of two- and three-dimensional nonlinear models of both wall and frame structures. Collapse sensitivity studies considered the possibility of the proposed component being used throughout the reference SFRS, as well as the "mixing" of proposed components and reference components within the reference SFRS. The following parameters were identified as critical for establishing equivalency in seismic collapse resistance:

- Deformation capacity (ultimate deformation) - Δ_U

- Strength (ratio of measured ultimate strength, Q_M to design strength, Q_D) - $R_Q = Q_M/Q_D$

- Initial stiffness (ratio of measured initial stiffness, K_I, to design stiffness, K_D) - $R_K = K_I/K_D$

- Effective ductility capacity (ratio of ultimate deformation, Δ_U, to effective yield deformation, $\Delta_{Y,eff}$) - $\mu_{eff} = \Delta_U/\Delta_{Y,eff}$.

These four performance parameters are based on measured properties of reference and proposed components, determined from cyclic-load testing of component test specimens. Figure 2 illustrates cyclic-load test data, the envelope curve of these data, and component properties based on the envelope curve. Multiple test specimens are required and statistical properties (e.g., median values) of performance parameters are used to evaluate component equivalency.
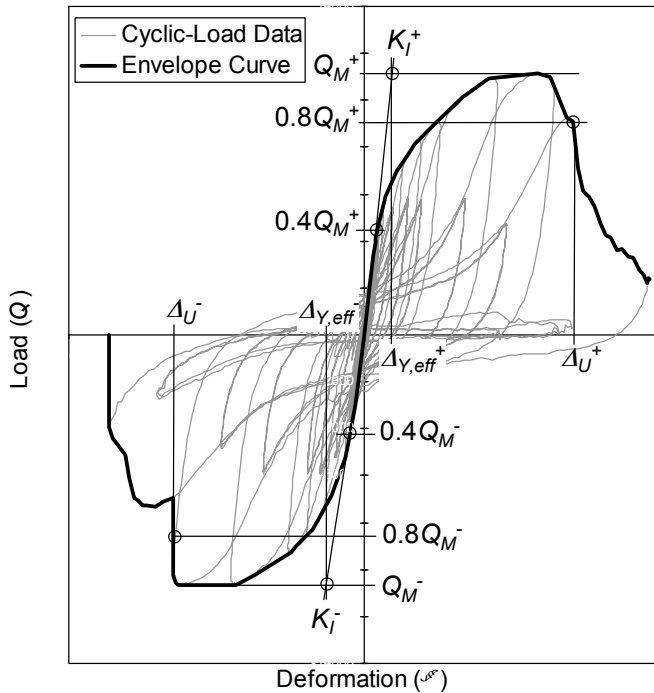

Figure 2. Illustration of cyclic-load test data, envelope curve and maximum load, Q_M, effective yield deformation, $\Delta_{Y,eff}$, ultimate deformation, Δ_U, and initial stiffness, K_I, parameters, for a component test specimen.

Component deformation capacity and strength are the most important parameters affecting the collapse safety of a seismic-force-resisting system. Initial stiffness, in general, has less of an effect on collapse safety, but was included as a key parameter because of its fundamental relation to ASCE/SEI 7-10 design processes, including (1) story drift limits, (2) the second-order stability coefficient, (3) the distribution of force demands to components within a statically indeterminate structural system, and (4) other seismic checks such as those related to horizontal and vertical stiffness irregularities. The effective ductility parameter is the ratio of ultimate to effective yield deformation.

The ultimate deformation, Δ_U, is the primary parameter the Component Methodology for judging component deformability. Nevertheless, effective ductility is still important for preventing inconsistencies in the nonlinear hysteretic behavior of components (e.g. ensuring a reasonable level of component energy dissipation capacity) and potential stiffness and strength irregularities that could result when elastic code-based seismic design procedures are utilized.

Monotonic-load test data are required in addition to cyclic-load test data to ensure that the proposed component has sufficient monotonic deformation capacity. The combination of monotonic-load and cyclic-load test data helps to distinguish between different characteristics of component strength deterioration, such as cyclic versus in-cycle degradation, which can influence the system collapse safety.

Development of Component Testing Requirements

Component testing requirements were drawn from the requirements of the FEMA P-695 Methodology and ASTM E2126-09 (ASTM 2009), tailored to meet the needs of the Component Methodology. Cyclic-load and monotonic-load testing requirements address the number of component configurations that need to be tested, the number of test specimens per configuration, and the selection of load histories for cyclic-load testing.

Cyclic-load test data are the primary basis for establishing equivalency of proposed and reference components. Since the measured component strength and deformation capacity may differ depending on the cyclic-load history applied, guidelines for the selection and comparison of loading histories are needed to ensure that performance parameters of the proposed and reference components are appropriately compared. Accordingly, the Component Methodology ensures that the loading history used to test the proposed component be at least as damaging (quantified in terms of accumulated deformation imposed on the specimen) as the loading history used to test the reference component.

Development of Probabilistic Acceptance Criteria

Acceptance criteria were developed to ensure that a seismic-force-resisting system containing full or partial replacement of proposed components would have equivalent (or better) resistance to seismic-induced collapse as the same system containing reference components alone. Specifically, these criteria require that the ground-shaking intensity large enough to cause a 10% probability of collapse in the seismic-force-resisting system is equivalent in both cases. This requirement is consistent with the probabilistic concepts of the FEMA P-695 Methodology, which require less than 10% probability of collapse under the code-defined maximum considered earthquake (MCE_R) ground motions.

While based on probabilistic equations and results from numerical collapse sensitivity studies, the resulting criteria were made to be deliberately simple. The principal acceptance criterion is that the factored median deformation capacity of the proposed component must be as large as, or larger than, the median deformation capacity of the reference component. The required margin between the proposed and reference component median deformation capacities is defined by two penalty factors that account for uncertainties associated with component test data and design requirements, and differences in strength. The penalty factors are unity when the uncertainties and differences in strength are relatively small.

Additional acceptance criteria are provided to ensure that the proposed and reference components have comparable values of initial stiffness when implemented in the reference SFRS, and that the effective ductility of the proposed component is at least 50 percent of the effective ductility of the reference component.

Applicability Criteria

The Component Methodology of FEMA P-795 is intended to apply to a broad range of component types proposed for use in any of the existing seismic-force-resisting systems of ASCE 7, subject to the following applicability criteria that address the suitability of the reference seismic-force-resisting system (SFRS), including adequacy of reference component design criteria and testing data, the adequacy of proposed component design criteria and testing data, and characteristics of the proposed component that would permit use of the Component Methodology:

1. Design requirements information and test data should be collected or developed for proposed and reference components sufficient to:

    *   Determine applicability of the Component Methodology.

    *   Determine values of all parameters required by the Component Methodology.

2. The reference SFRS should comply with the collapse performance criteria contained in the FEMA P-695 Methodology. For the purpose of the Component Methodology, it is assumed that existing SFRS of ASCE 7 comply with these criteria.

3. Quality of test data and design requirements of the referenced and proposed components should be rated based upon:

    *   Completeness and robustness of tests and design requirements.

    *   Confidence in tests results and design requirements.

4. The proposed component, reference component, and reference SFRS should comply with the following general criteria:

    *   Component Boundary. The boundary between components and the balance of the reference SFRS should be defined such that:

        o   Component test specimens and their connections to the reference SFRS are unambiguously defined.

        o   Testing boundary conditions are clearly established and realistically represent the interaction between the component and the reference SFRS.

        o   Component boundary is the same for the proposed and reference components.

        o   Transfer of forces across the component boundary is essentially the same for the proposed and reference components.

    *   Balance of the Structure. The balance of the reference SFRS and the distribution of force and deformations beyond the component boundary are essentially unchanged by replacement of reference components with proposed components.

    *   Seismic Isolators and Dampers. Proposed and reference components are not intended for use as either an isolator unit, as defined by Chapter 17 of ASCE 7, or a damping device, as defined by Chapter 18 of ASCE 7.

    *   Component Properties. Load-deformation properties of proposed and reference components are substantially independent of the rate of loading (i.e., components are not velocity dependent).

    *   Component testing. Nonlinear (inelastic) response of the components can be reliably measured by cyclic-load and monotonic-load testing.

    *   Component Similarity. Proposed and reference components have a comparable range of seismic load resistance and capacity to support vertical loads (for components that support vertical loads).

Practical application of the Component Methodology will likely be limited to those components for which there is sufficient quality and quantity of test data for judging equivalency.

Example Application of the Component Methodology - Prefabricated Wall Component

During development of the Component Methodology, a "beta test" of the methodology was performed using cyclic-load test data of a pre-fabricated wall component. These test data were provided to the ATC-63-1 Project by the manufacturer of the pre-fabricated wall component, a proprietary product which has been approved by the International Code Council Evaluation Services (ICC ES) for use in light-frame wood construction. As such, the beta test example application allows a qualitative comparison of the acceptance criteria of the Component Methodology with those currently used by ICC ES to evaluate new products.

In accordance with the request of the manufacturer, the specific product is not identified, but it is representative of a number of similar proprietary wall products of different manufacturers, including Weyerhauser, Hardy Frame, Simpson Strong Wall, and others, that have very high-aspect ratios. These products are typically used at the boundaries of large openings in walls of light-frame wood construction for which wall length is limited (e.g. garage wall lines in residential construction), and are particularly common in regions of high seismicity or strong winds.

Product anonymity greatly restricted the information available to the project. Experimental data were limited to cyclic-load test results for three specimens of a single configuration of the proposed wall component. As such, these data were not sufficient to permit a complete beta test evaluation of the Component Methodology. Nonetheless, the cyclic-load test data were useful in terms of testing the methods for processing cyclic-load test data, extracting key parameters from these data, and evaluating these parameters using the acceptance criteria of the Component Methodology.

Although incomplete as a full application of the Component Methodology, this beta test illustrates an application of the methodology that could be used by manufacturers as a preliminary check of the seismic adequacy of new products. In such cases, prototypical specimens of a representative (or critical) configuration would be fabricated, subjected to cyclic-load testing, and performance evaluated using the acceptance criteria of the Component Methodology. At least two test specimens are needed to verify repeatability of key parameter values.

Description of Pre-Fabricated Wall Component

The prefabricated wall component (proposed component) is intended for use in light-frame wood construction (i.e., Bearing Wall System A.15, Table 12.2-1 of ASCE/SEI 7-10). The single configuration of the proposed component of this example is 9 feet (108 inches) tall and very short in length. As

noted previously, product information was limited and the details of proposed component configuration, materials and construction were not available, but would be required for a complete evaluation of the prefabricated wall component.

Component Methodology Applicability Evaluation

The applicability of the Component Methodology is based largely on the comparison of characteristics of components of the reference system, in this case, the light-frame wood wall system, and those of the proposed component. While the applicability of the methodology could not be rigorously evaluated, due to lack of specific design and configuration data for the proposed component, the Component Methodology is expected to generally apply to these types of prefabricated wall components.

Of particular importance to judging the applicability of the methodology to high-aspect wall components is the definition of the component boundary, and related boundary conditions which must be realistically represented by the test setup. The boundary of pre-fabricated wall components is typically well defined by the manufacturer's drawings of typical details for anchoring and connecting these products to the balance of the seismic force resisting system. These types of drawings are required to evaluate force transfer at the component boundary and for review of the adequacy of boundary conditions of proposed component test specimens.

Reference Component Test Data

In this example, reference component test data are based on CUREE cyclic-load testing of nailed wood shear wall panels (Line et al. 2008). The Line et al. data set contains data from a total of 80 test specimens, including 48 wall tests that were compiled as part of the ICC-ES effort to develop the acceptance criteria of AC-322 (ICC-ES, 2007), as well as results of an additional 32 wall tests. To create the reference component data set, data were removed for walls with openings, stapled walls, and walls with box nails, leaving a total of 65 wall tests in the final database. These 65 wall tests are considered representative of components of the reference SFRS (i.e., Bearing Wall System A.15, Table 12.2-1 of ASCE/SEI 7-10).

Table 1 shows summary statistics of performance parameters calculated from the 65 wall tests of the reference component. Summary statistics include the median and lognormal standard deviation (variability) of the four key performance parameters of the Component Methodology. Section 4.4 of FEMA P-795 provides in-depth discussion of the specific test data and other background information used to establish summary statistics of reference component parameters.

Table 1. Summary Statistics of Reference Component Parameters (from Table 4-3, FEMA P-795).

Summary Statistic	R_Q (Q_M/Q_D)	R_K (K_I/K_D)	μ_{eff} $(\Delta_U/\Delta_{Y,eff})$	Δ_U (in./in.)
Median	2.7	1.0	6.3	0.035
Variability	0.11	0.42	0.38	0.16

The median parameter values of Table 1 tell us that representative components of the light-frame wood wall system have, on average, a component "overstrength" of about 2.7, as compared to $\Omega_O = 3$ for system overstrength, an effective ductility of about 6.3, as compared to $R = 6.5$ for response modification (for linear elastic design of the system), and an ultimate drift ratio of about 3.5 percent. In this example, the design stiffness (K_D) of the reference component is based on the allowable shear and the permissible deflection of Equation (23-2) of the 2006 *IBC* (ICC 2006).

Proposed Component Design Requirements

Pre-fabricated wall product information was limited in this example to design load and design stiffness data for a single configuration of the proposed component. The design load (for ASD) is $Q_D = 580$ lbs and the design stiffness is $K_D = 1,514$ lbs./in., based on a drift of 0.38 inches (i.e., drift ratio of 0.0035 in./in.) at the ASD design load.

In general, manufacturers of pre-fabricated wall components provide detailed product guides that describe installation requirements, including typical anchorage and connection details, as well as tables of design loads and other design criteria for all configurations of the product. Presumably, these types of design and construction information would be available for full evaluation of the proposed component, as required by the Component Methodology to establish design loads and evaluate the quality of design requirements.

Proposed Component Test Data

Pre-fabricated wall test data were limited in this example to the results of cyclic-load testing of three test specimens of the same configuration. Monotonic-load test data were not available for this product. Full evaluation of the proposed component product would require cyclic-load test data for multiple configurations representing the full range of possible configurations of the prefabricated wall component, and possibly monotonic-load data.

The cyclic-load test data were plotted, envelope curves fitted and values of load, deformation and stiffness parameters determined form the envelop curves, in accordance with the criteria illustrated in Figure 2. An example plot of cyclic-load test loops, the envelop curve and certain parameter values are

shown in Figure 3 (for Test Specimen No. 1). Test loops are stable and similar for each of the three test specimens.
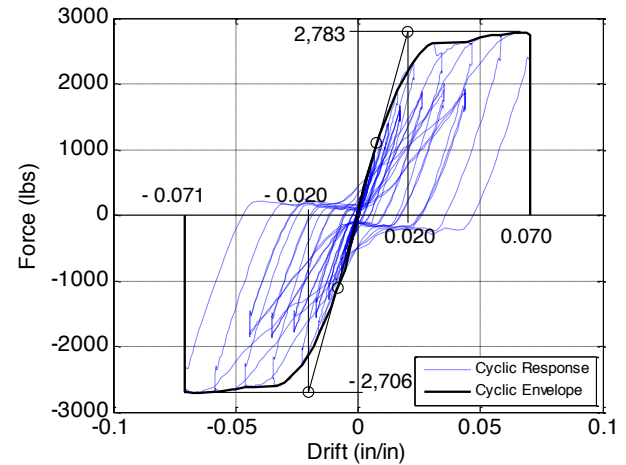

Figure 3. Example plot of cyclic-load test data, envelope curve and parameter values of Test Specimen No. 1 of the proposed component.

Table 2 summarizes values of the strength ratio (R_Q), the stiffness ratio (R_K), the effective ductility (μ_{eff}) and ultimate deformation capacity (Δ_U) obtained from the cyclic-load test data of the three proposed component test specimens, and shows the summary statistics (median and variability) for these four performance parameters.

Table 2. Test Specimen Data and Summary Statistics of Proposed Component Parameters.

Specimen or Summary Statistic	R_O (Q_M/Q_D)	R_K (K_I/K_D)	μ_{eff} $(\Delta_U/\Delta_{Y,eff})$	Δ_U (in./in.)
Specimen 1	$\dfrac{2,745}{580}$	$\dfrac{1,248}{1,514}$	$\dfrac{0.071}{0.020}$	0.071
Specimen 2	$\dfrac{2,730}{580}$	$\dfrac{1,211}{1,514}$	$\dfrac{0.070}{0.021}$	0.070
Specimen 3	$\dfrac{2,810}{580}$	$\dfrac{1,317}{1,514}$	$\dfrac{0.065}{0.020}$	0.065
Median	4.8	0.83	3.4	0.068
Variability	0.02	0.04	0.03	0.05

The relatively small values of variability in Table 2 confirm the stable nature of parameters obtained from different test specimens of the same configuration, but are insufficient to assess parameter variability of all possible configurations of the proposed components because of the very limited number of tests. Parameter variability would be expected to be significantly larger if based on the full range of configurations of the proposed component.

Median values of performance parameters in Table 2 are assumed in this example to be generally representative of the median properties of proposed component. That is, median values of parameters would be expected to be about the same, if based on the full range of proposed component configurations. On this basis, the median values of Table 2 tell us that the proposed component has an ultimate drift ratio of about 6.8 percent, significantly greater than the 3.5 percent median ultimate drift ratio of the reference system, a "component overstrength" of about 4.8, significantly greater than the 2.7 median overstrength of the reference component, and an effective ductility of about 3.4, significantly less than the 6.3 median effective ductility of the reference component. Only the effective stiffness ratio, $\widetilde{R}_K = 0.83$, of the proposed component is similar to that of the reference component.

So, is the proposed component equivalent? That is, would the collapse performance of a light-frame wood wall system be the same, or better, if the pre-fabricated wall component with much greater ultimate displacement capacity, but much less effective ductility (and significantly greater overstrength) is substituted at one or more locations in the light-frame wood wall system? The following sections use the quality rating and acceptance criteria of the Component Methodology to answer this question.

Design and Test Data Quality Ratings

Similar to the methods of FEMA P-695, the Component Methodology of FEMA P-795 requires quality ratings to be assigned to the design requirements and to the test data of both reference and proposed components. Quality rating categories are Superior, Good or Fair, as defined by the criteria given in Section 2.7 of FEMA P-795.

Quality ratings influence the value of the quality "penalty factor," P_Q, which is used with certain acceptance criteria to explicitly account for differences in collapse probability due to differences in the uncertainty of proposed and reference component properties.. The value of the penalty factor, P_Q, is 1.0, or less (i.e., no penalty) when proposed components are judged to have the same, or better, quality rating (i.e., equal or less parameter uncertainty) as those of the reference component.

In this example, reference component test data are rated Superior, since wood shear wall research (such as that of the CUREE Wood Project) has produced an unparalleled amount of useable test data.

There was not sufficient information to rate the quality of proposed component test data due to the limited number of available test data. For the purpose of this beta test, proposed component test data are rated as Good, assuming all required cyclic-load and monotonic-load tests would be performed.

In this example, reference component design requirements are rated as Good. While wood design criteria and associated construction requirements are reasonably well established, actual performance of light-frame wood wall systems has varied significantly in past earthquakes.

There was not sufficient information to rate the quality of proposed component design data. For the purpose of this beta test, proposed component design requirements are rated as Superior, assuming product information, including design and construction requirements, would be found comparable to that typically of pre-fabricated wall products. The higher quality rating assigned to the proposed, pre-fabricated, component recognizes the greater quality control (i.e., less uncertainty) that can be achieved in products manufactured in shops, provided they are properly installed in the field.

Evaluation of Component Equivalency

This section discusses the acceptance criteria of Section 2.8 of FEMA P-795, and illustrates the use these criteria to evaluate whether the pre-fabricated wall component should be judged equivalent to nailed wood shear walls, and thus appropriate for use in light-frame wood construction.

As noted previously, this example evaluation of equivalency is necessarily incomplete due to the limited amount of test data available (i.e., only three specimens of a single configuration). Nonetheless, results still provide a meaningful evaluation of equivalency to the degree that the single configuration used in this beta test represents the balance of configurations of the pre-fabricated wall component of interest.

The Component Methodology evaluates equivalency of proposed and reference components grouped in terms of comparable characteristics, so-called "performance groups." In general, only one performance group need be used to evaluate component performance, but this group must include a sufficient number of different component configurations to represent the full range of product characteristics. In this example, only one performance group was deemed necessary to evaluate performance.

While the properties of the reference component are based on a number of different configurations, judged sufficient to represent nailed wood shear walls, the properties of the proposed component are based on only a single configuration which does not fully represent the product of interest. To illustrate the acceptance criteria of the Component Methodology, median properties of the proposed component are assumed to be the same as those determined from the evaluation of the single configuration.

The following sequence of checks parallels the flow of the acceptance criteria of Section 2.8 of FEMA P-795 used to evaluate component equivalency. In general, component equivalency is evaluated by comparison of proposed

component properties and reference component properties, determined from cyclic-load testing. The one exception is the last check in the sequence which compares component deformation capacity determined from monotonic-load testing.

Check of Ultimate Deformation Capacity

The first and most important check of component equivalency is the comparison of proposed and reference component ultimate deformation capacity, using median values of capacity determined from cyclic-load testing. The Component Methodology requires that the median ultimate deformation satisfy Equation (1):

$$\tilde{\Delta}_{U,PC} \geq \tilde{\Delta}_{U,RC} \; P_U \; P_Q \tag{1}$$

As reported earlier, the median ultimate deformation ($\tilde{\Delta}_{U,RC}$) of the reference component, expressed in terms of drift ratio, is 0.035 in./in. (from Table 1), and the median ultimate deformation ($\tilde{\Delta}_{U,PC}$) of the proposed component, expressed in terms of drift ratio, is 0.068 in./in. (from Table 2).

In Equation (1), the strength penalty factor, P_Q, is based on the ratio of median strength ratios of proposed and reference components. The ratio of proposed component strength (i.e., overstrength) is 4.8 (from Table 2) and the ratio reference component strength is 2.7 (from Table 1) and the ratio of these values is:

$$\frac{\tilde{R}_{Q,PC}}{\tilde{R}_{Q,RC}} = \frac{4.8}{2.7} = 1.78 \tag{2}$$

This equation shows that the proposed component has significantly more "overstrength" than the reference component which could adversely affect collapse performance, especially if reference and proposed components are "mixed" in the reference SFRS. From Table 3, the value of the penalty factor is $P_Q = 1.24$, for the ratio of 1.78 from Equation (2).

Table 3. Penalty Factor to Account for Differences in Strength (copy of Table 2-4 of FEMA P-795)

Penalty Factor for Differences in Strength (P_Q)[1]			
$\tilde{R}_{Q,PC} / \tilde{R}_{Q,RC}$	P_Q	$\tilde{R}_{Q,PC} / \tilde{R}_{Q,RC}$	P_Q
0.50	1.88	1.10	1.00
0.60	1.55	1.20	1.00
0.70	1.31	1.30	1.04
0.80	1.14	1.40	1.09
0.90	1.00	1.50	1.13
1.00	1.00	1.80	1.24
1.10	1.00	2.00	1.32

1. Linear interpolation is permissible between tabulated values.

The values of strength penalty factors given in Table 3 are based on probabilistic acceptance criteria studies (Appendix C of FEMA P-795) that quantified the trade-off between having extra (or less) overstrength, and the ultimate displacement capacity of the proposed component required to achieve the same (low) probability of collapse given MCE_R ground motions. In this case, an extra 24 percent of ultimate displacement capacity is required to offset an extra 78 percent of overstrength.

Since the ratio of Equation (2) exceeds 1.2, the Component Methodology requires force-controlled and capacity designed elements of the reference SFRS to be designed to develop the expected strength of the proposed component (i.e., 4.8 x 580 lbs. = 2,784 lbs.).

Note. Regardless of the value of the ratio of Equation (2), the Component Methodology requires the attachment of the proposed component to the balance of the reference SFRS to be strong enough to develop the full ultimate strength of the proposed component, such that inelastic behavior occurs in the proposed component, and not at the boundary between the proposed component and the balance of the reference SFRS.

From Table 4, the value of uncertainty penalty factor is $P_U = 1.0$, based on the quality ratings described in the previous section (i.e., design quality rating of the proposed component is Better than that of the reference component and the test data quality rating of the proposed component is Good).

Table 4. Penalty Factor to Account for Uncertainty (copy of Table 2-3 of FEMA P-795)

Penalty Factor for Uncertainties (P_U)			
Quality Rating of Proposed Component Test Data[1]	Quality Rating of Proposed Component Design Requirements Relative to the Reference Component[1]		
	Better[2]	Same[3]	Worse[4]
Superior	0.95	1.00	1.15
Good	1.00	1.05	1.25
Fair	1.15	1.25	1.40

1. Quality ratings are computed in accordance with Table 2-1 and Table 2-2 of FEMA P-795).
2. Better: Respective quality ratings of proposed and reference component design requirements are Superior and Good.
3. Same: Respective quality ratings of proposed and reference component design requirements are Superior and Superior, or Good and Good.
4. Worse: Respective quality ratings of proposed and reference component design requirements are Good and Superior, or Fair and Good.

The values of uncertainty penalty factors given in Table 4 are based on probabilistic acceptance criteria studies (Appendix C of FEMA P-795) that quantified the trade-off between having

more (or less) uncertainty of test data and design requirements, and the ultimate displacement capacity of the proposed component required to achieve the same (low) probability of collapse given MCE_R ground motions. In this case, differences in the quality ratings of proposed and reference component essentially cancel out ($P_U = 1.0$).

Incorporating values of summary statistics and penalty factors into Equation (1) leads to the following check of ultimate deformation equivalency:

$$0.068 \geq 0.035\,(1.0)(1.24) \geq 0.043 \quad \underline{\underline{OK}} \quad (3)$$

As shown, this requirement is easily satisfied since the median ultimate deformation capacity of the pre-fabricated wall is quite large.

Check of Ultimate Deformation Capacity for Outlier Configurations

In addition to the Equation (1) check of median ultimate deformation of the proposed component ($\widetilde{\Delta}_{U,PC}$) of all proposed component configurations (of the performance group interest), the median ultimate deformation of each individual configuration of the proposed component ($\widetilde{\Delta}_{Uj,\,PC}$) must also meet the requirement of Equation (4):

$$\widetilde{\Delta}_{Uj,PC} \geq \left(1-1.5\sigma_{\Delta_U,RC}\right)\!\left(\widetilde{\Delta}_{U,RC}\right)P_U\,P_Q \quad (4)$$

Equation (4) checks for "outlier" configurations, by requiring the ultimate deformation capacity of each individual proposed component configuration to be within 1.5 lognormal standard deviations of the median ultimate deformation capacity of the reference component. This acceptance criterion could not be checked in this example, since Equation (4) requires summary statistics for the full range of proposed component configurations and test data were only available for a single configuration.

Check of Effective Initial Stiffness

The Component Methodology requires the median initial stiffness ratio of the proposed component be reasonably similar to the median initial stiffness ratio of the reference component, in accordance with Equation (5):

$$0.75 \leq \frac{\widetilde{R}_{K,PC}}{\widetilde{R}_{K,RC}} \leq 1.33 \quad (5)$$

Requiring similarity of proposed and reference component initial stiffness ratios effectively defines an acceptable range of design values of proposed component initial stiffness (e.g., for checking the effects of component substitution on the initial stiffness distribution of the reference SFRS).

As reported earlier, the median initial stiffness ratio ($\widetilde{R}_{K,RC}$) of the reference component is 1.0 (from Table 1) and the median initial stiffness ratio ($\widetilde{R}_{K,PC}$) of the proposed component is 0.83 (from Table 2).

Incorporating these values into Equation (5) leads to the following check of initial stiffness equivalency:

$$0.75 \leq \frac{0.83}{1.0} \leq 1.33 \quad \underline{\underline{OK}} \quad (6)$$

As shown, the initial stiffness requirement is satisfied. While actual initial stiffness of the proposed component is much less than that of the reference component, the design value of initial stiffness of the proposed component is also much less than that of the reference component.

Check of Effective Ductility

The Component Methodology requires that the median effective ductility of the proposed component be not less than one-half of the median effective ductility of the reference component, in accordance with Equation (7):

$$\widetilde{\mu}_{eff,PC} \geq 0.5\,\widetilde{\mu}_{eff,RC} \quad (7)$$

As reported earlier, the median effective ductility ($\widetilde{\mu}_{eff,RC}$) of the reference component is 6.3 percent (from Table 1) and the median initial stiffness ratio ($\widetilde{\mu}_{eff,PC}$) of the proposed component is 3.4 percent (from Table 2).

Incorporating these values into Equation (7) leads to the following check of effective ductility:

$$3.4 \geq (0.5)6.3 \geq 3.2 \quad \underline{\underline{OK}} \quad (8)$$

As shown, the effective ductility requirement is satisfied, although with a modest margin, essentially using all of the proposed component's relatively large ultimate displacement capacity to meet the effective ductility criterion.

Check of Ultimate Deformation Capacity (using Monotonic-Load Data)

The Component Methodology requires the proposed component to have a comparable, or better, ultimate displacement capacity as that of the reference component for monotonic (pushover) loading, in accordance with either Equation (9) or Equation (10):

$$\widetilde{\Delta}_{UM,PC} \geq \widetilde{\Delta}_{UM,RC}\,P_U\,P_Q \quad (9)$$

$$\widetilde{\Delta}_{UM,PC} \geq 1.2\,D_C\,\widetilde{\Delta}_{U,RC}\,P_U\,P_Q \quad (10)$$

In Equation (10), the cyclic-load test ultimate deformation ($\widetilde{\Delta}_{U,PC}$) may be used in lieu of the monotonic-load test ultimate deformation ($\widetilde{\Delta}_{UM,PC}$).

Since monotonic data are not available, Equation (10) is used to evaluate this requirement, where monotonic-based median ultimate displacement ($\widetilde{\Delta}_{UM,PC}$) is taken as equal to the cyclic-based median ultimate displacement ($\widetilde{\Delta}_{U,PC}$) of 0.068. The value of D_C is 1.0, based on the use of CUREE cyclic-load test protocol to perform the cyclic-load tests of the reference component. Values of the penalty factors, P_U and P_Q, are as previously defined.

Incorporating these values into Equation (10) leads to the following check of ultimate displacement capacity for monotonic-load (low cycle) conditions:

$$0.068 \geq 1.2(1.0)0.035(1.0)(1.24) \geq 0.052 \quad \underline{OK} \quad (11)$$

As shown, the check of "monotonic" ultimate displacement capacity is satisfied, using the cyclic-load test ultimate deformation of the proposed component as a conservative surrogate for the monotonic-load test ultimate deformation of the proposed component. The acceptable result of Equation (10) indicates that monotonic-load tests are not required for the given configuration of the prefabricated wall component.

Summary of Example Results

This example "beta test" of the Component Methodology of FEMA P-795 evaluated a pre-fabricated wall product intended for substitution in light-frame wood wall construction. This product, representative of a number of similar proprietary products, is typically used at the boundaries of large openings in walls of light-frame wood construction for which wall length is limited. As such, these products tend to be relatively slender and quite flexible.

Processing of cyclic-load test data showed the pre-fabricated wall component to have relatively large ultimate displacement capacity, but much less effective ductility (and significantly greater overstrength) than a corresponding segment of a nailed wood shear wall. Despite these differences, the Component Methodology found the proposed component to be "equivalent" in terms of collapse performance.

Although incomplete (due to limited data), the findings of this example application of the Component Methodology suggest that the pre-fabricated wall component would be appropriate for use in light-frame wood shear wall construction. The findings of this example are consistent with those of the ICC ES that found the pre-fabricated wall product complies with the acceptance criteria of AC 322 (ICC ES 2008).

Conclusion and Recommended Future Work

The recommended Component Methodology described in this paper provides a rational basis for evaluating the seismic performance equivalency of new components that are proposed as substitutes for selected components in a currently approved seismic-force-resisting system. Proposed components found to be equivalent by the Component Methodology can be substituted for components of a reference seismic-force-resisting system (reference SFRS), but are still subject to design requirements and seismic design category restrictions on the use of the reference system.

A potential hindrance to broad application of the Component Methodology (or any "equivalency" method) is a lack of sufficient number of quality test data for reference components (i.e., "benchmark" test data on components of current code-approved systems). A very real need exists to identify and compile component test data for as many systems as possible in ASCE/SEI 7-10.

Acknowledgments and Disclaimer

References

ASCE, 2010. *Minimum Design Loads for Buildings and Other Structures*, ASCE/SEI 7-10, American Society of Civil Engineers, Washington, D.C.

ASTM, 2009. *Standard Test Method for Cyclic-(Reversed) Load Test for Shear Resistance of Vertical Elements of the Lateral Load Force Resisting System for Buildings*, ASTM ES 2126-09, American Society of Testing and Materials, West Conshohocken, Pennsylvania.

FEMA, 2011. *Quantification of Building System Performance and Response Factors - Component Equivalency Methodology*, FEMA P-795, prepared by Applied Technology Council, prepared for the Federal Emergency Management Agency, Washington, D.C.

FEMA, 2009. *Recommended Methodology for Quantification of Buildings System Performance and Response Parameters*, Report No. FEMA P-695, prepared by Applied Technology Council, prepared for the Federal Emergency Management Agency, Washington, D.C.

ICC, 2006. *International Building Code*, International Code Council, Inc., Country Club Hills, IL.

ICC-ES, 2007. *Acceptance Criteria for Prefabricated, Cold-Formed, Steel Lateral-Force-Resisting Vertical Assemblies*, AC 322, International Code Council Evaluation Services, Whittier, California.

Line, P., Waltz, N. and Skaggs, T., 2008. "Seismic equivalency parameters for engineered wood frame wood structural panel shear walls," *Wood Design Focus*, Vol. 18, No. 2.

NIST, 2010. *Evaluation of the FEMA P-695 Methodology for Quantification of Building Seismic Performance Factors*, NIST GCR 10-917-8, prepared by the NEHRP Consultants Joint Venture for the National Institute of Standards and Technology, Gaithersburg, Maryland.