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SIMPLIFIED CYCLE-BASED DESIGN OF EXTREMELY LOADED STRUCTURES

R. Weitzmann

Bauhaus-University Weimar, Institute of Structural Engineering, 99423 Weimar, Germany
E-mail: ruediger.weitzmann@bauing.uni-weimar.de

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Abstract. *The design of safety-critical structures, exposed to cyclic excitations demands for non-degrading or limited-degrading behavior during extreme events. Among others, the structural behavior is mainly determined by the amount of plastic cycles, completed during the excitation. Existing simplified methods often ignore this dependency, or assume/request sufficient cyclic capacity. The paper introduces a new performance based design method that considers explicitly a predefined number of re-plastifications. Hereby approaches from the shakedown theory and signal processing methods are utilized. The paper introduces the theoretical background, explains the steps of the design procedure and demonstrates the applicability with help of an example.*

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1 INTRODUCTION

For structures facing cyclic excitation, e.g. in seismic regions, the demand for non-degrading or limited-degrading structures with ductile behavior is rising. Samples are buildings of lifeline and high technology industries that have to maintain their operability during and after the event. Furthermore, it is required to restrict the amount of accepted damage to limit repair efforts. These requirements define a minimum performance or capacity level that have to be maintained after excitation. In these cases the application of isolation technologies is not always appropriate and necessary. Structural dissipating strategies can be applied as well, if a performance level can be adjusted that utilizes plastic reserves for energy dissipation, while assuring a predefined damage limit [1-3].

Problems arise if the capacity of the members degreases rapidly after some cycles with damaging (plastic) potential, as illustrated in Fig 1. Hereby, substantial damage is caused from several re-plastifications [4]. Besides failure prevention, high degrading levels are often not acceptable in structures. Requirements can reach from a purely elastic behavior to higher but limited damage levels that can be characterized by maximum plastic excitations and the number of plastic cycles or re-plastifications.

This paper describes a simplified design procedure that considers the following circumstances and objectives:

- Planned application for performance levels operability and immediate occupancy
- Application for structures with elasto-plastic cross sectional behavior (at plastic hinges) like r/c-, src-, steel- or mixed type structures
- Avoidance of equivalent replacement systems, use of all kind FE structural models, especially of models proposed by codes
- No a-priori necessity for regular systems
- No modification of loads by global reduction factors
- Including a response abstracting step (rely on the statistical character of earthquake excitations, no direct dependency to a specific time history like in non-linear dynamic analysis)
- Reduction of responses considering acceptable deformations and numbers of re-plastifications
- Individual scalability for each point of the structure
- Capacity validation and design at local points, including estimation of global behavior
- Reflection of cross sectional behavior including force interactions
- Direct verification of performance, direct feedback of design decisions to the structural behavior
- Direct support and application of capacity design principles
- Use of simple and fast calculation algorithms (mainly on a linear basis even if the analysis is non-linear itself, manual approaches should be considered for simple structures)
- Evaluation of effects caused by damping or isolation devices
- Optionally: direct design improvement by application of optimization technologies

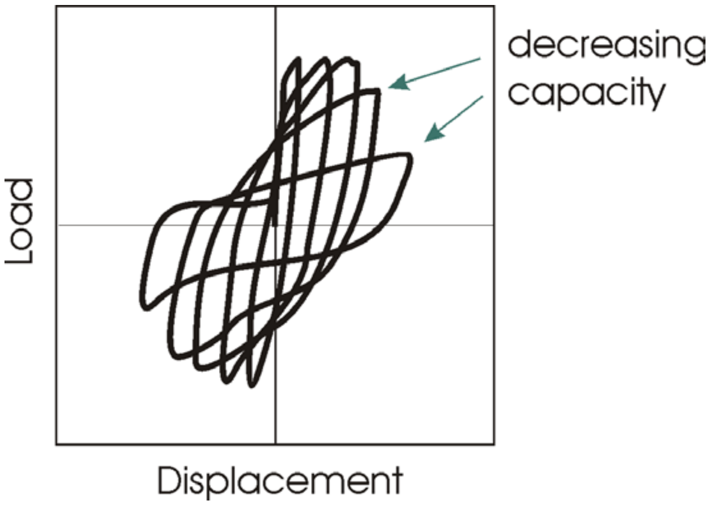


Figure 1 Deterioration after plastic cycles

2 GENERAL DESIGN PRINCIPLE

The design method is derived from a combination of shakedown theory and signal evaluation methods that consider amounts of re-plastifications. The first concept was already designated for the design of seismic excited structures. As specified in [5] the shakedown state denotes an appropriate performance level for structures with limited damage levels. Utilizing the shakedown state in structural design ensures the following behavior for the structure:

- Use of plastic reserves for energy dissipation for elasto-plastic structures
- Establishment of a stable residual state after a limited number of plastic excitations
- Avoidance of damage accumulations, no cycle fatigue
- No alternating plastifications (re-plastifications)
- No progressive plastifications (ratcheting)
- Assurance of full operability at the same safety level (after-shock resistance)

The underlying principle of shakedown is characterized as follows:

After a limited number of inelastic deformations a stable residual state will be constituted, all further behavior is elastic.

The response of a structure can be divided into an elastic and a residual part e.g. for stresses

$$\sigma = \sigma_{el} + \sigma_r \tag{1}$$

thus both parts can be regarded separately and can be superposed. The elastic part is represented by an envelope response. As can be seen in Fig. 2, this assumption is realistic for elastic plastic structures because such structures behave linear elastic in the first stage even if a certain inelastic deformation history was attended. In most design cases, the exact damage history is not of interest, only the assessment of their impacts. Simple linear elastic – plastic model assumptions are appropriate considering a residual state that represents the amount of damage resulting from the history. The stiffness degradation has to be regarded. The necessary cross-sectional parameters can be determined in a pre-phase with use of simple fiber models (push over analysis for the cross section).

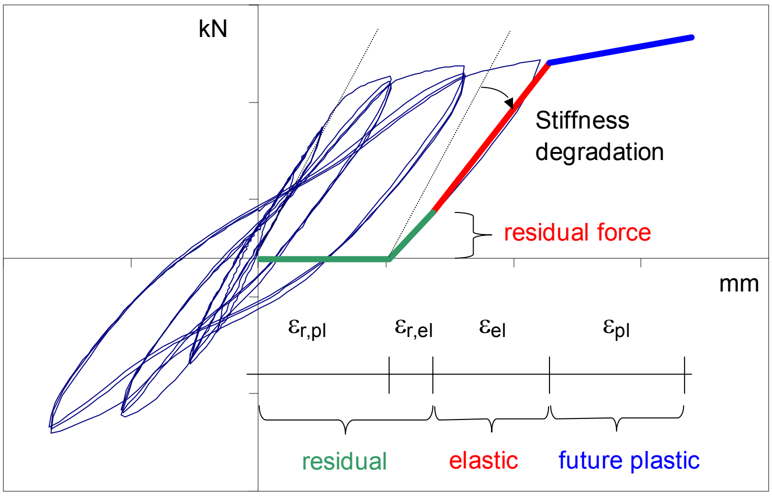


Figure 2 Derivation of material law

The application of shakedown theory leads to conservative solutions compared with other design strategies accepting plastic hysteretic behavior. Starting from this, load impacts beyond the shakedown limit level result in inelastic hysteretic behavior combined with re-plastification cycles in plastic hinges.

The enhancement to the shakedown based approach is the implementation of signal reduction procedures considering the number of re-plastifications. The principle is almost similar to approaches that reduce spectra data on a cycle basis. These approaches were originally specified to support the application of linear response spectrum methods for non-linear structures [7,8]. The idea is to reduce the resistance of the structure to a certain level, from that only a predefined amount of load peaks effect hysteretic behavior. With the choice of the parameter “Number of re-plastifications” a simple method to scale and influence the perspective damage can be established.

However, the application within this procedure provides a main difference. In a first step contrary to the mentioned methods the reduction procedure refers not to the loads but to the structural response. This includes that for estimation of the elastic part, the calculation of a linear time history has to be performed. Commonly this is not a problem because physically linear time history analysis is well established, theoretically clear and therefore the results are not as widespread as in nonlinear procedures.

It is the convention herein, to refer the reduced envelope procedure not on complete cycles (complete hysteresis) but to the number of re-plastifications (changed direction of inelastic deformation) that will be signed as n in the following text. The purely elastic case will be referred as a special case with n=0. The original procedure considering only the shakedown state is indicated by n=1. A complete cycle of inelastic deformation is characterized by n=2 and so forth.

Accordingly the application of cycle-reduced spectra can be established. This scenario is sketched in Table 4. The main principle of reducing the maximum signal amplitude by cycle approaches is illustrated in Fig 3. Further approaches can consider a probabilistic treatment for reducing the elastic envelope.

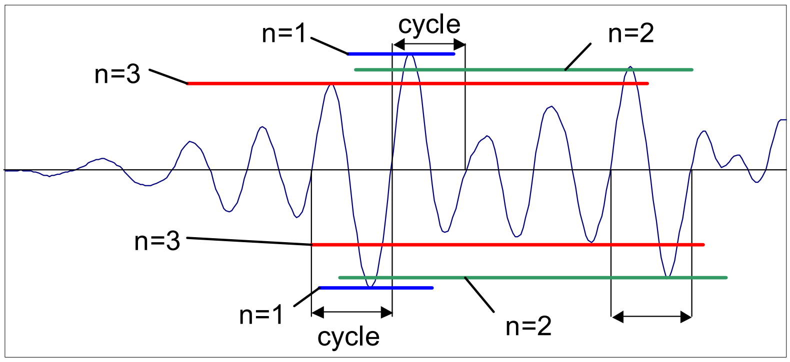


Figure 3 Figure 3 Signal reduction using number of re-plastifications

3 DESIGN PROCEDURES

Short chart descriptions can be found in Table 1 and 2. The first strategy (designated as strategy V) is conceived regarding structural verification. The mechanical system, the loads and masses are determined traditionally. According to this the complete detailing has to be provided. Important is the determination of regions for potential plastification, according to Capacity Design rules. Out of this, the resistance (supply) of the structure can be calculated. After calculating the elastic response (either with time history or simplified analysis), the derived envelop will be reduced due to the targeted number of re-plastifications. In a limit state analysis, the resistance factor r and the residual state are derived. The factor scales linearly the resistance parameters of a pre-defined cross-sectional resistance distribution, e.g. for reinforced concrete structures, this can be interpreted as changing the reinforcement. The resulting behavior has to be evaluated with respect to the plastic hinge distribution and loading. For structural safety, the resistance factor r must be greater than 1.0.

The second strategies follows a design and dimensioning objective (noted strategy D). The core sequences are almost similar to procedure V. However, the advantage is the shorter pre-design, that requires only an assessment of the structural stiffness distribution. The calculation of the elastic envelope is according to procedure V. This is the basis to determine an appropriate kinematic mechanism, by placing limit conditions to the potential hinge regions. After this, the residual state and the appropriate resistance factor are calculated. The superposition of the elastic and residual results gives the design relevant internal forces. The hinge distribution has to be evaluated and the detailing can take place. In a last step the previously made stiffness assumptions should be compared with the design. The calculation should be repeated in an iterative process in case of great differences as indicated in Tab. 1 and 2.

Table 1 Design procedure V (Verification strategy)

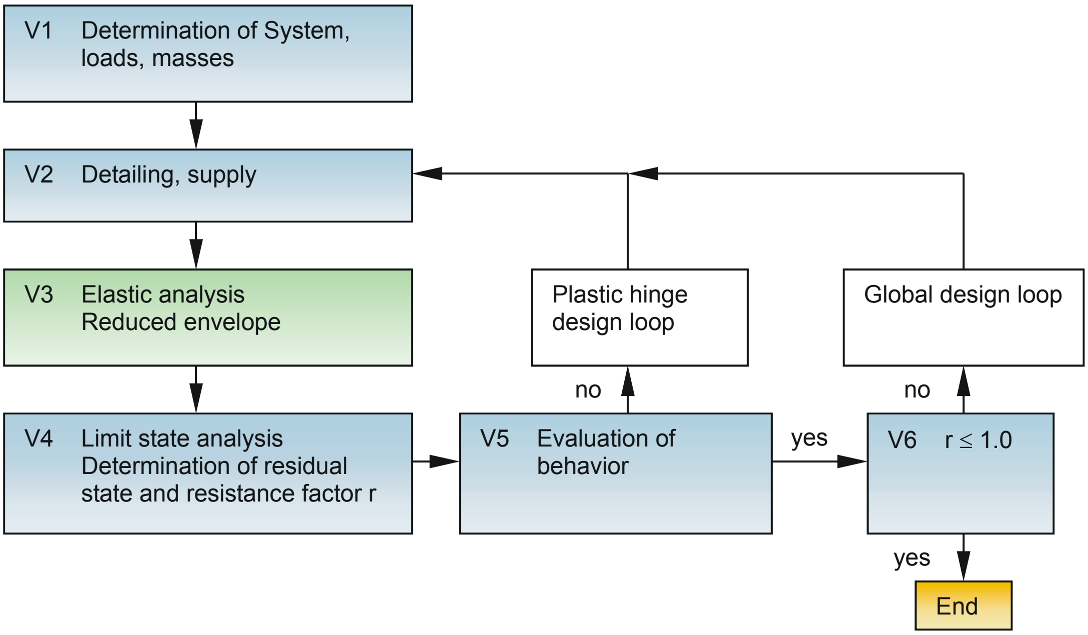
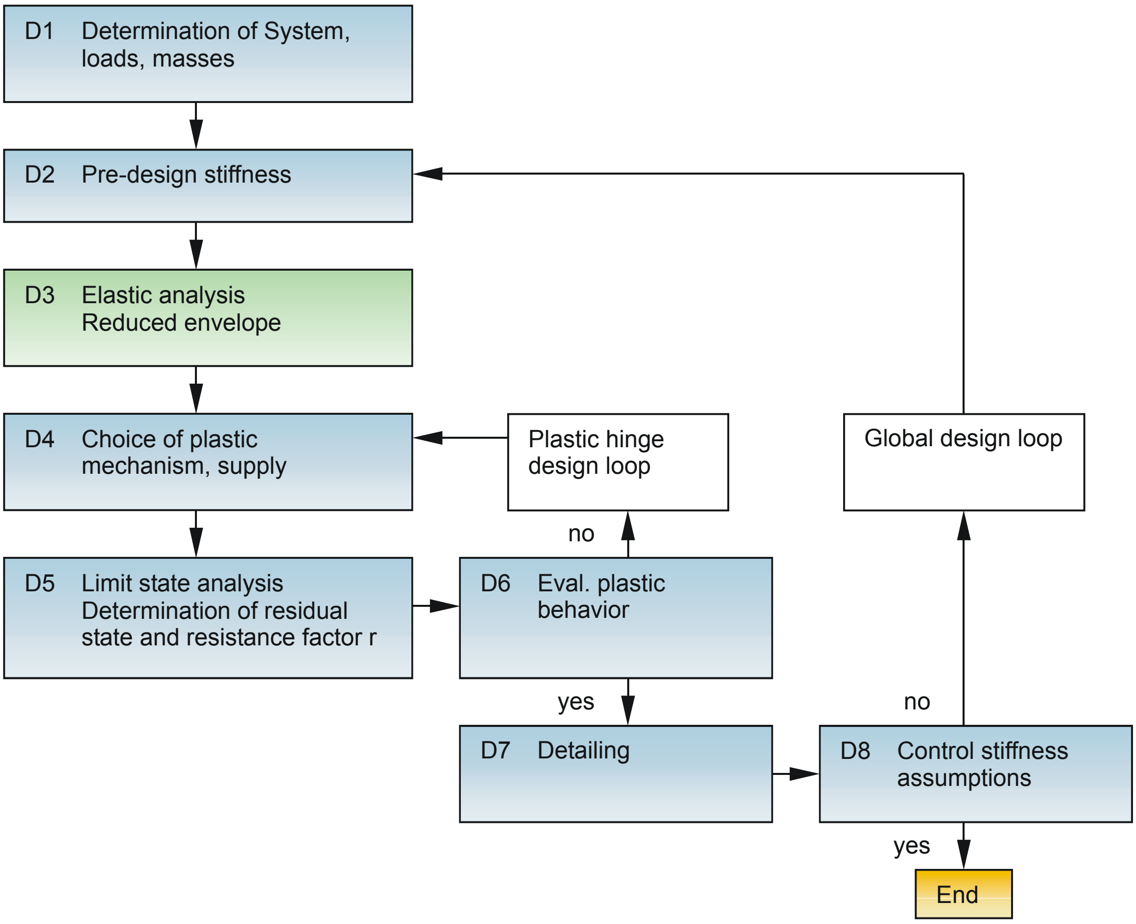


Table 2 Design procedure D (Dimensioning strategy)



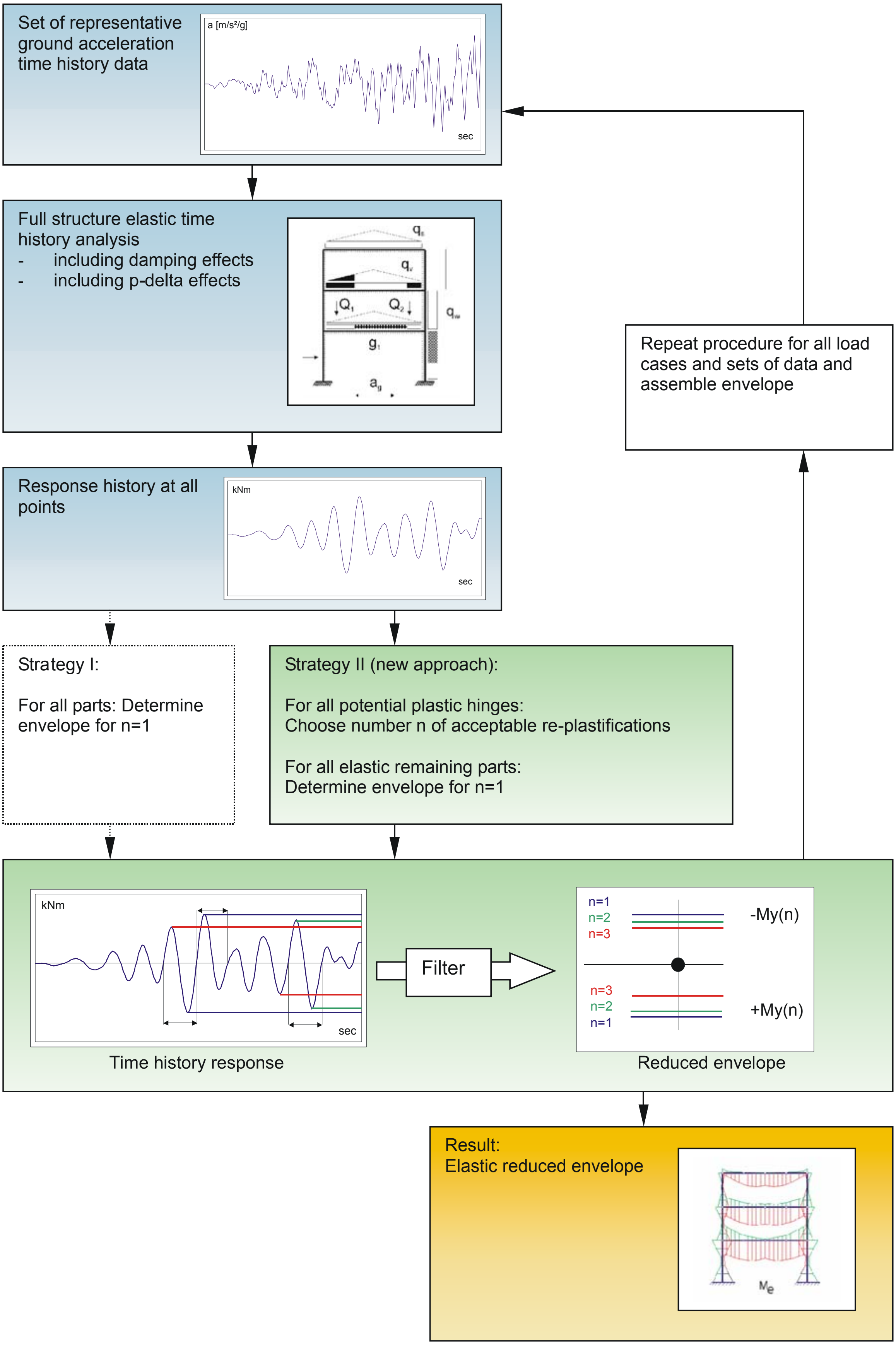
In Tabs. 3 and 4 two options for the derivation of the elastic envelope solution in the design procedures are presented in more detail. The derivation of the elastic envelope is illustrated in Table 3 for the strategy that utilizes linear time history responses. For an approximate respect of the statistical distribution of the response parameters, sets of time history data should be evaluated. For any of this the elastic responses are calculated for the structure. In the traditional procedure, the maximum and minimum response peaks are determined at each point of the structure (Strategy I). In an advanced procedure (Strategy II), the response can be selected at the plastic hinge regions with respect to the number of re-plastifications n. For all other points, that are supposed to remain elastic during the excitation, the envelop calculation can omitted or the envelop is simply determined for n=1. Consequently, a reduced envelop response is derived. The calculation has to be repeated for all selected sets of time history loads. Then the elastic envelop consists of extreme results for all time history sets.

In Tab. 4 a method is sketched for utilizing cycle based response spectra data for calculating the elastic envelope. The calculation of the spectral values must be altered, so that the extreme responses are selected with respect to the cycles in the linear response. This step mainly corresponds to the time history evaluation method given in Tab. 3, but for SDOF systems only. If the procedure is repeated for different structural periods in the SDOF, the corresponding response values are collected to form a reduced spectrum. This spectrum is the basis to calculate the elastic response of the entire structure to the selected excitation, to calculate the envelop solution. Also in this procedure, several sets of excitations can be beneficially included.

In Tab. 5 the sequence of calculating the limit state and the appropriate residual state is presented. The shown approach bases on optimization technologies. The procedure consists of two separate steps. First, the calculation of the adaptive resistance factor r, that scales the resistance parameters in the cross sections. This value is used to scale the resistance (here indicated exemplarily as the constant part of the plasticity conditions s_U). Secondly, the appropriate residual stress distribution can be calculated with help of a quadratic optimization approach. This calculation can be done with the reduced elastic envelope $s_{el,n}$ that gives an approximate average plastic performance overview. Using the non-reduced envelop $s_{el,1}$ (for n=1) instead, is adequate to indicate the extreme results for the plastic deformations. The later use of the residual state information within the design procedures V and D are sketched shortly within Tab. 5.

The results obtained by this procedures are conservative. That means, that the indicated number of re-plastifications is an upper bound that will never be exceeded. The real responses due to single dynamic events can be smaller than calculated within this procedure. This is due to the simplification to neglect time effects and therefore to reduce the response to their envelope values. The effects can be caused by plastic dissipation that takes place prior to the actually considered extreme events in the time history. Such plastic dissipation reduces the amplitudes of the subsequent response peaks, so that the caused plastic deformations can be smaller than those calculated with the elastic envelope simplification. However, the maximum expectable plastic deformations can be assessed conveniently.

Table 3 Elastic analysis and derivation of the reduced envelope for strategy based on time history analysis



Set of representative ground acceleration time history data

Full structure elastic time history analysis
- including damping effects
- including p-delta effects

Response history at all points

Strategy I:

For all parts: Determine envelope for n=1

Strategy II (new approach):

For all potential plastic hinges: Choose number n of acceptable re-plastifications

For all elastic remaining parts: Determine envelope for n=1

Repeat procedure for all load cases and sets of data and assemble envelope

Time history response

Filter

Reduced envelope

Result: Elastic reduced envelope

Table 4 Elastic analysis and derivation of the reduced envelope for strategy based on response spectrum analysis

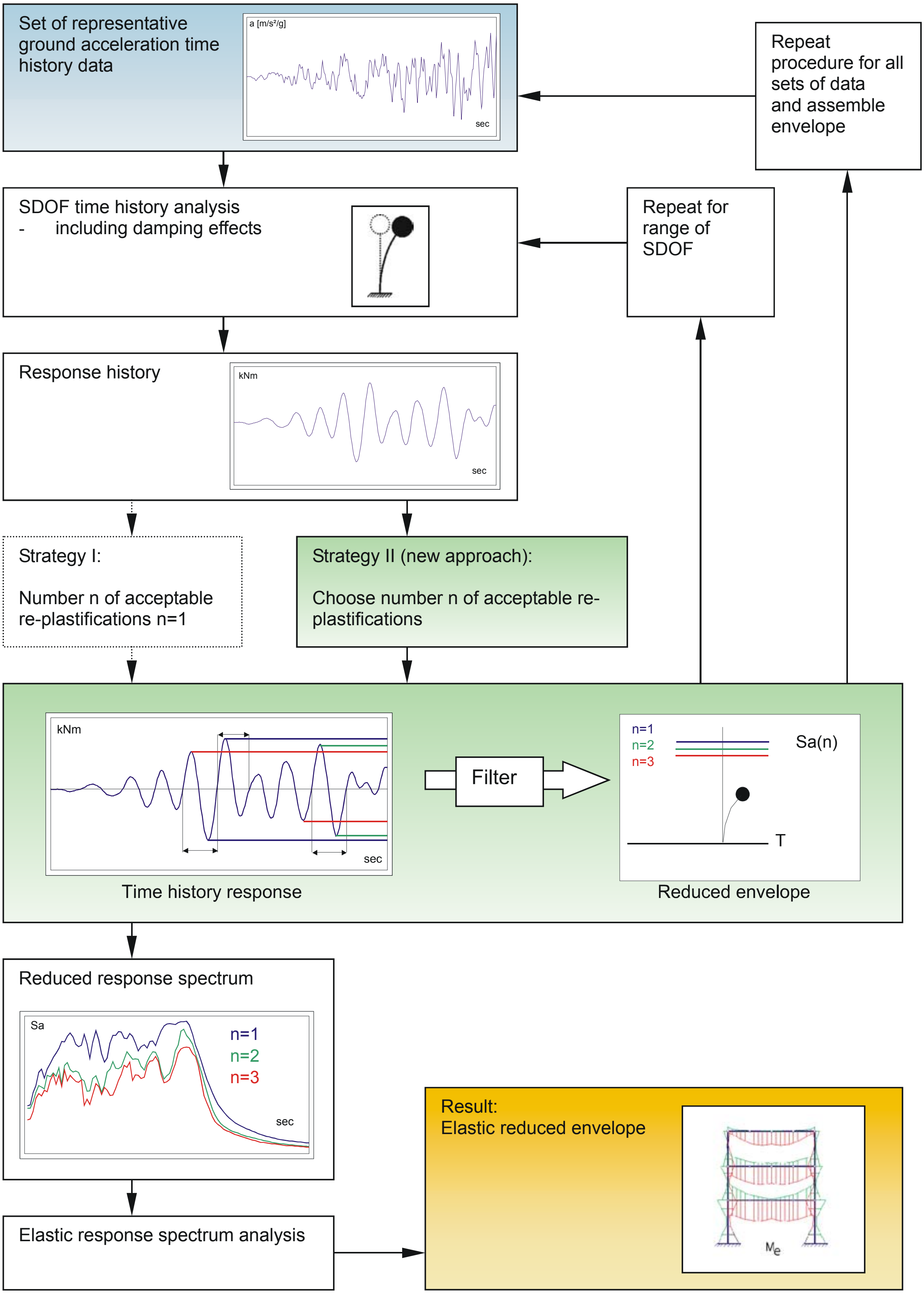
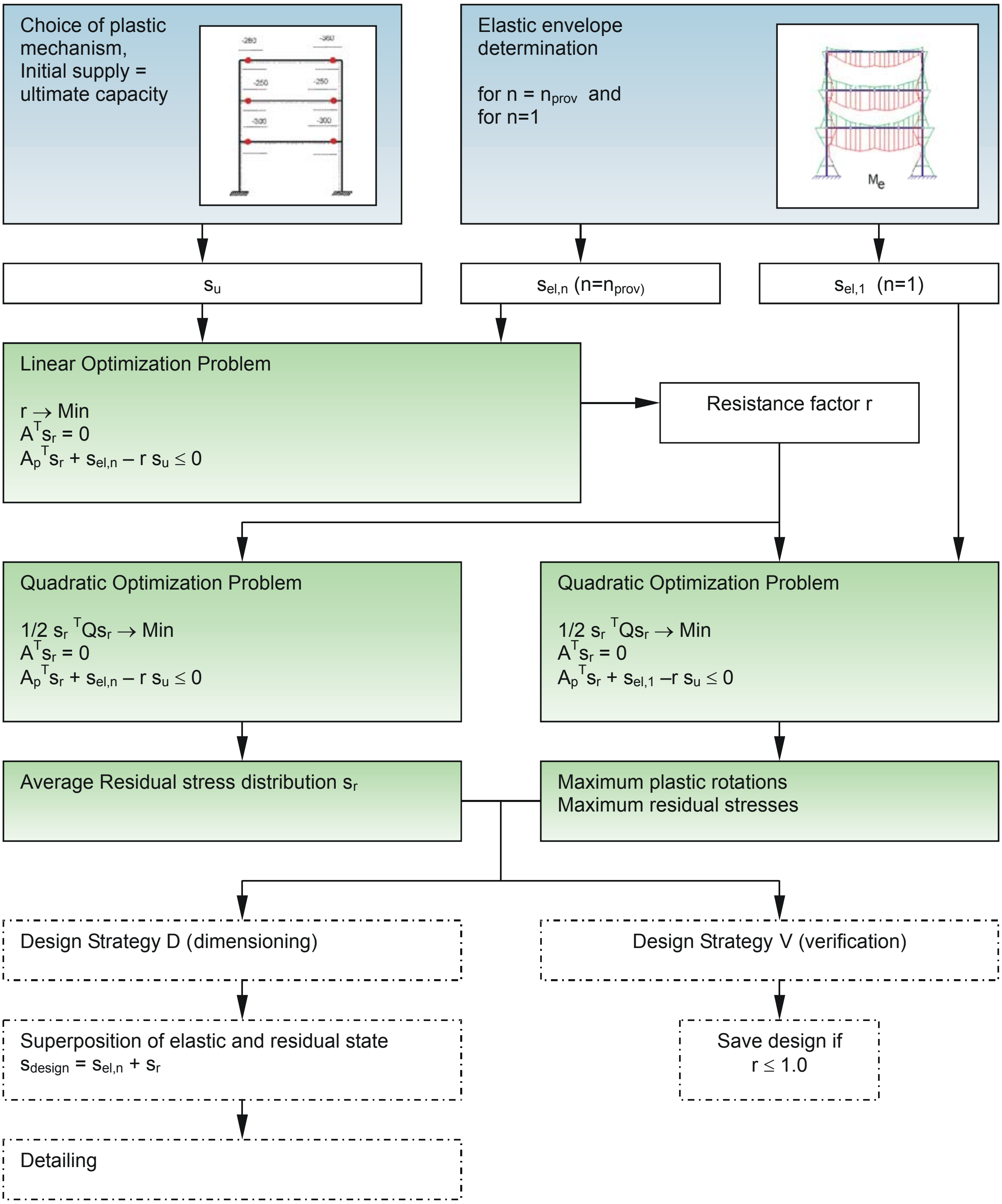


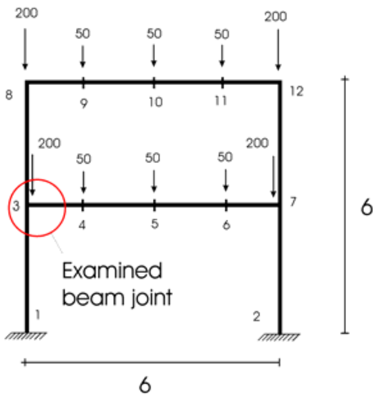
Table 5 Limit state analysis



4 EXAMPLE

This Example is to demonstrate the application of Design Procedure D (according to Tab. 2). A simple beam-column structure is given, exited by an artificial ground acceleration (Tab. 6). For simplicity the usually recommended load case studies are not performed, thus excitations only from one time history and only from one direction are considered. For result discussion, the behavior at the end of the beam in the first floor (Point 3) is most focused. After performing an elastic time history analysis the elastic envelope is calculated.

Table 6 Step D1/D2. System, loads, masses, pre-design stiffness



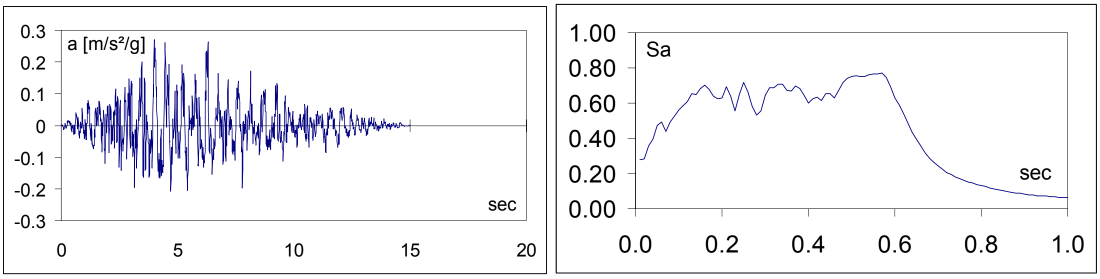
Columns:
EA $= 7.5 \cdot 10^6$ kN
EI $= 1.56 \cdot 10^5$ kNm^2

Beams:
EA $= 3 \cdot 10^7$ kN
EI $= 2.7 \cdot 10^5$ kNm^2

Lumped Masses at nodes: 10 t

$T_1 = 0.28$ sec Damping 5%

Artificial ground acceleration and response spectrum



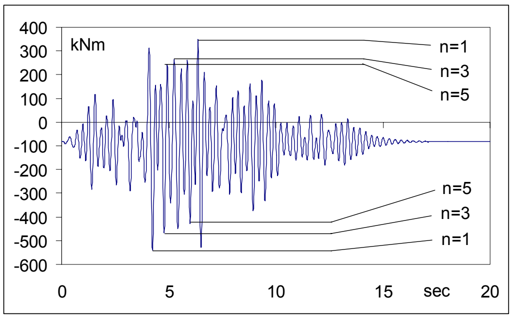
The response values will be used to assemble the elastic envelope solution according to the sequence in Tab. 3. After choosing the plastic mechanism the reduced envelope values can be filtered. For demonstration in this example three different numbers of re-plastification (1,3 and 5) are chosen (Tab. 7). The position of the potential plastic hinges and the initial values of the moment capacities are given in Tab. 8.

The reduced elastic envelope is used to calculate the resistance factors. In Tab. 9 the resistance factors r according to their appropriate numbers of re-plastification n are shown. The theoretical case of total elastic behavior (n=0) is given for comparison. The residual forces are calculated as well.

Table 7 Step D3. Elastic analysis, elastic envelope

Calculation of
elastic time history

Determination of
envelope values
S_{elast}
including reduced
values at plastic
hinges according
to a selected re-plastification
number



Elastic moment history for beam joint, point 3
Marked: envelope for n=1,3,5

Table 8 Step D4 Choice of plastic mechanism and supply

Plastic hinges only
at the beam ends
(elastic ideal
plastic)

Choice of initial
moment capacity
distribution
at plastic hinges

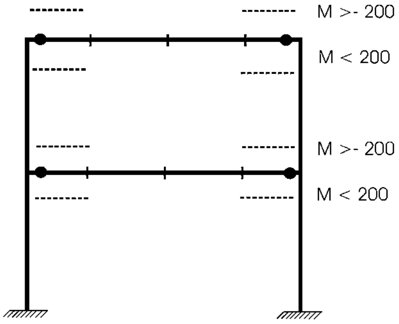
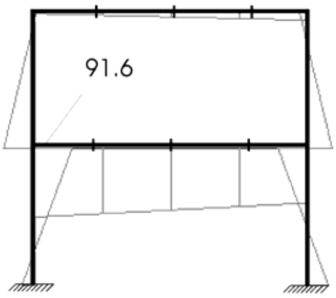


Table 9 Step D5 Calculation of limit state



Residual moment distribution S_{res} (n=5)
Max. expected plastic rotations (beam point 3)
$2.61 \cdot 10^{-3}$ rad (n=5)

Resistance factors:

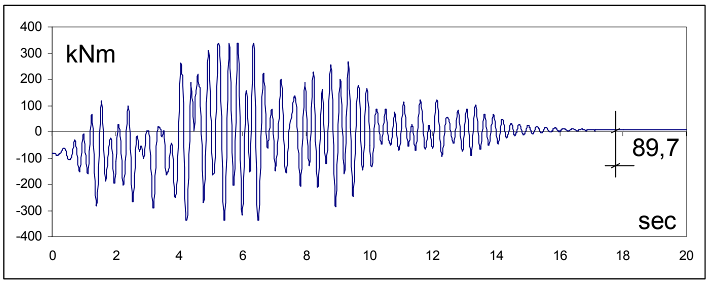
elastic behavior (for comparison)
r = 2.70 (n=0, 100% elastic)

non-linear behavior
r = 2.22 (n=1, 82% elastic)
r = 1.83 (n=3, 68% elastic)
r = 1.68 (n=5, 62% elastic)

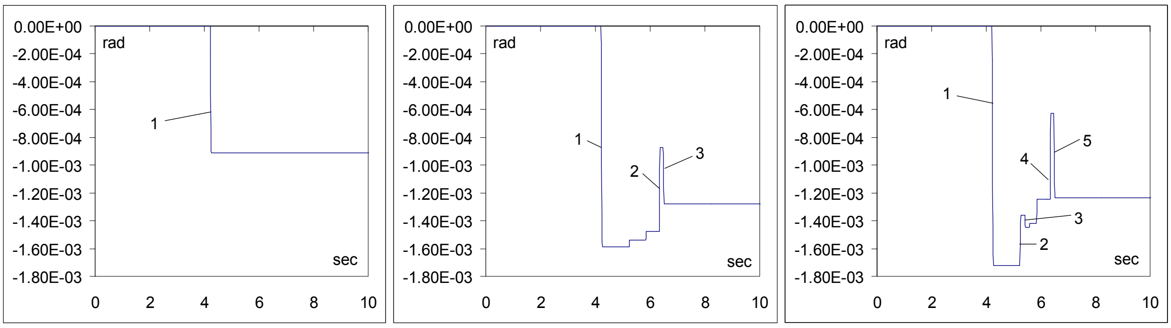
As can be seen in the diagram of Tab. 9 a non-uniform distribution of plastic response is generated. For better distribution of plastic deformations within the structure, a simple loop back to step D4 can be done to rearrange the initial moment capacity distribution and calculate the limit state again without considering the time history again. In computer implementations an automatic procedure for finding the optimal distribution with help of a programming approach can be included easily. Having an acceptable behavior, the procedure can be finished by superposing the residual state and the elastic envelope for the derivation of the design forces. The detailing can now be established according to Capacity Design rules.

To control how this design will perform during an earthquake an comparison with a non-linear dynamic analysis is provided here. It should be noted, that this step is not part of the design routine. The given ground acceleration of Tab. 6 is used as excitation. In Tab. 10 the bending moment history for *n*=5 and the plastic part of the rotations at the considered beam end (Point 3) are shown for different numbers of re-plastification. It can be outlined, that according to the design objective all accounts of re-plastification will stay below it's projected values. For this specific example the ultimate number of re-plastification is adjusted. This is not necessarily and always the case. The procedure just guarantees, that the ultimate number is not exceeded. As expected the maximum plastic rotations calculated by the limit state analysis (for case *n*=5 and $\kappa \leq 2.61\cdot$ 10-3) is not exceeded at the observed point. The calculated value of residual moment (89.7) is almost as calculated by the simplified approach (91.6).

Table 10 Proof with nonlinear dynamic analysis



Bending Moment at Point 3 for n=5
Marked: Residual moment



Plastic beam rotations at Point 3 for n = 1,3 and 5
Marked: changes in plasticity direction

5 CONCLUSIONS

The presented method has been proven to be efficient for the design of structures, that can resist a limited amount of plastic cycles. It utilizes the advantages of plastic dissipation while ensuring the safe performance during excitations. It can be used in the verification of existing structures or for new design. It has been shown, that either time history and simplified methods can be applied within the procedures.

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