PUSHOVER ANALYSIS OF RC BRIDGES USING FIBER MODELS OR PLASTIC HINGES

R. Monteiro[1], R. Ribeiro[2], M. Marques[1], R. Delgado[3] and A. Costa[4]

[1] *PhD Student, Dept. of Civil Engineering, Faculty of Engineering, University of Porto, Porto. Portugal*
[2] *Researcher, Dept. of Civil Engineering, Faculty of Engineering, University of Porto, Porto. Portugal*
[3] *Professor, Dept. of Civil Engineering, Faculty of Engineering, University of Porto, Porto. Portugal*
[4] *Professor, Dept. of Civil Engineering, University of Aveiro, Aveiro. Portugal*
Email: ricardo.monteiro@fe.up.pt , rui.andre.ribeiro@fe.up.pt, mario.marques@fe.up.pt, rdelgado@fe.up.pt, agc@ua.pt

ABSTRACT :

Non-linear static procedures, such as pushover-based ones, have been continuously refined and improved along the past few years as a complement or even as an alternative to dynamic time-history analysis. On that matter, great relevance has been given to the procedure of the method itself. By other words, effort has been put in studying the best way to obtain the equivalent necessary SDOF structure quantities towards the performance point attainment. Prior to those aspects, substantial interest remains on the computation of the pushover curve for the original MDOF structure, where modeling aspects come up decisively. This paper intends to readdress that issue from the modeling type point of view. Currently, most of the structural seismic analyses are carried out considering either fiber-based or plastic hinge structural models. Depending on the choice, distinct ways of considering the non-linear behavior of the elements are regarded and different parameters and calibration procedures need to be set. With the purpose of investigating the accuracy of both modeling possibilities, a parametric study is conducted on different bridge configurations, comparing pushover curves as well as NSP results which make use of those pushover curves. Application issues, such as advantages and/or limitations, in each of the modeling types are discussed. Accuracy is tested with the goal of finding out if the option for one of the models is either desirable or irrelevant.

KEYWORDS: Pushover, nonlinear static procedure, modeling, fiber-based, plastic hinges, bridges.

1. INTRODUCTION

When studying the structural behavior of bridges under earthquake loading, an adequate characterization and interpretation of the damage demand requests the consideration of the nonlinear behavior of the structural elements. Given that current seismic design and assessment codes emphasize the need for more accurate deformation analyses, instead of the common force-based ones, there is a clear advantage in using nonlinear features to obtain a more precise characterization of deformation measures such as ductility demand.
The use of nonlinear static procedures, based on the computation of pushover curves, as a tool for seismic assessment of bridges, constitutes a possible way of including the aforementioned features. Within this kind of framework, the modeling aspects assume relevant meaning given that the pushover curve will be greatly influenced by the model itself. Currently, two modeling possibilities are taken into account: fiber or plastic hinge based ones. Advantages and pitfalls of the pushover type of analysis, carried out according to EC8, making use of those two different modeling approaches, will be presented herein.
Starting with the description of the considered modeling possibilities, the study carries on with a set of comparative analyses towards a better understanding of the complexity associated to this sort of approach in a structural behavior assessment context. The influence of different issues involved in a nonlinear static procedure, such as the inelastic modeling of structural behavior, definition of plastic hinge length and position or the definition of the lateral load pattern and selection of control node, is discussed thoroughly herein.
Subsequently, a study on the seismic behavior of RC bridges using pushover analysis is carried out. A set of seven different structural configurations were selected and two modeling approaches for the nonlinear behavior were considered: concentrated plasticity with moment-curvature for cross section behavior and distributed plasticity with a fiber modeling approach for the element behavior.
In order to perform a comparison of the different pushover strategies, some seismic response measure parameters, such as deck displacements and bending moments, piers and abutments shear forces, were selected. Results were somewhat statistically treated and conclusions and final remarks were taken on the way to identify eventual advantages and limitations of the different nonlinear modeling modalities.

2. PUSHOVER ANALYSIS AND MODELING POSSIBILITIES

Current design codes and guidelines already start to require the consideration and corresponding identification on how plasticity influences the structural response, together with the energy dissipation capacity characterization. Ideally, according to what is majorly accepted, seismic analysis should be dynamic time-history based. However, computational effort and complexity associated to this sort of approach makes it still less feasible than other simplified alternatives. One of these alternatives is the pushover-based Nonlinear Static Procedures (NSP), such as well known Capacity Spectrum Method or N2 or other recent improved proposals, such as Modal Pushover Analysis or Adaptive Capacity Spectrum Method. NSPs have gained supporters during the past few years due to its proved capacity of, in a simple manner, providing nonlinear performance parameters without going through the demand of a dynamic time-history analysis. The first step within the application of a given NSP is the computation of the pushover curve for the structure, which may be obtained using a fiber or plastic hinge based model.

2.1. Plastic hinge models

When considering a concentrated plasticity model, the nonlinear behavior of the bar elements is located in a rotational spring in both extremities of the elastic behavior part of the element. Indeed, and regarding the particular application to bridges, studies carried out in the recent past have shown that bridge piers have a clear tendency to assume a nonlinear behavior in well defined regions, which somewhat enables such plastic hinge approach. Nevertheless, this kind of simplified model should be handled with care given that accuracy of the results may be compromised when the user does not have reasonable know-how on calibration of inelastic elements parameters. Limitations in the use of plastic hinge modeling assumptions can be found in work from Charney and Bertero (1982) or Bertero *et al* (1984), among others. The assumption of the concentrated plasticity zones for the structural elements, with corresponding plastic hinges formation is currently used to estimate the real deformation capacity, taking duly account of the material nonlinear behavior, Figure 1.

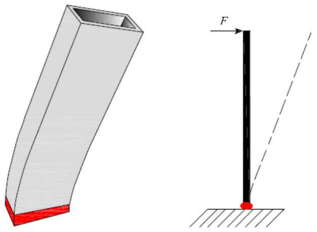


Figure 1 Plastic hinge formation (on the base of a pier subjected to horizontal load)

Using this kind of approach, the nonlinear analysis process becomes greatly simplified, namely to what concerns the numerical data processing. The deformation capacity of the element depends on the ultimate curvature and plastic hinge length, hence, different criteria used for the definition of these parameters may imply a different deformation level. Within the current work, different possibilities for the definition of the plastic hinge length are considered in a short complementary parametric study. The characterization of a plastic hinge requires a moment-curvature diagram to be defined, or other "equivalent" one, which is obtained from the monotonic loading of the cross section. The carried study has used, for the plastic hinge models' analyses, the bar finite element program SAP2000 and BIAX, developed at University of Porto, for the moment-curvature behavior curves.

2.2. Fiber based models

A structural model that includes nonlinearity in a distributed fashion, using finite fiber elements, is able to characterize in higher detail the reinforced concrete elements and thought to capture more accurately response effects on such elements. Geometrical and material properties are the only required ones as input. According to Casarotti and Pinho (2006) a fiber model manages to represents the propagation of the nonlinear effects over the cross section of the element as well as along its extension. Consequently, higher accuracy in the structural damage estimate is attained, even for the case of high inelasticity levels. Fiber based analysis may have numerical solution using a stiffness or flexibility-based formulation. Differences between the two possibilities have been studied in Papaionnou et al (2005) and the choice for the classic formulation based on the stiffness matrix developed by Izzuddin (2001) has been made. For this kind of models analysis, the fiber-based finite elements software package SeismoStruct (2006), which basically performs 3D finite element modeling, with behavior prediction for high displacement levels of structures subjected to static or dynamic loading, has been chosen. Material nonlinearity and second order effects are taken into account. A stiffness based cubic formulation is used to represent the development of the inelasticity along the element, together with axial load and transverse deformation interaction. Numerical integration makes use of two Gauss points per element, and the reinforced concrete cross section is discretized in fibers, as represented in Figure 2.

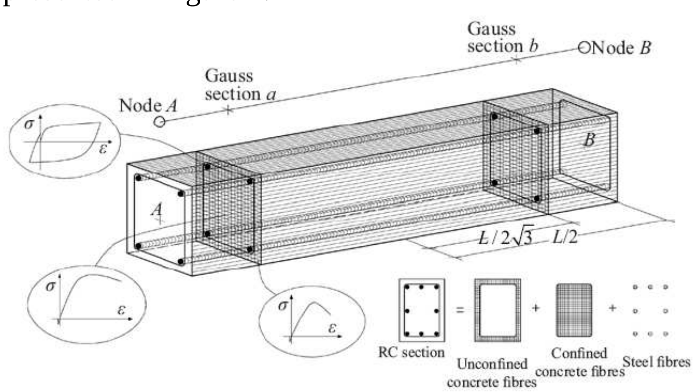


Figure 2 Reinforced concrete element discretization – fiber modeling approach (Casarotti and Pinho, 2006)

2.3. Model calibration

The option for any of the exposed modeling possibilities involves important initial assumptions such as the plastic hinge length and location. A calibration study focusing on those parameters, as well as a comparison of the cross section moment-curvature curves, coming from both approaches, has been carried out, leading to the following conclusions:

- The plastic hinge length can be estimated according to several proposals available in current literature and design codes or guidelines. Three alternatives have been analyzed: Kappos (1991), Priestley (2007) and EC8 (CEN, 2005). The approach from Kappos, Eqn. 2.1, has been adopted, for the simple fact that it provided the intermediate results among the three, and given the fact that no significant differences coming from the use of any of the three approaches has been found.

$$l_p = k \cdot l_c + l_{sp} \tag{2.1}$$

where $k = 0.2\left(\frac{f_{su}}{f_{sy}} - 1\right) \leq 0.04$, l_c is the distance from the critical section to the inflexion point of the element deformed shape, and $l_{sp} = 0.022 f_{sy} \phi_{Asl}$.

- Another relevant parameter, from a concentrated plasticity perspective, is the plastic hinge location in the element, which, according to the used software package, SAP2000, can be at any position within the ending portion of the discretized bar. It has, though, been verified that, apart from being negligible, differences are mainly related to the maximum attainable base shear capacity rather than the curve shape itself.
- For the capacity curve computation, which is the main result of a pushover analysis, the need for an accurate consideration of the behavior of the piers' cross sections is obvious, given that the piers will be the bridge elements with nonlinear behavior. The calibration study showed that, either for hollow or solid cross sections, and different loading conditions, the moment-curvature behavior given by both of the programs (plastic hinge or fiber-based) is quite similar, leaning possible the proceeding with the pushover based comparative study.

3. CASE STUDY

Seven reinforced concrete bridge structures have been considered for the parametric study, originally considered within the research project PREC8 – Bridge Research Programme (Guedes, 1997, Pinto et al., 1996) and modeled later on used in a nonlinear static analyses context by Casarotti et al. (2005). The set includes short/long, 200m or 400m deck length, and regular/irregular configurations, with piers 1, 2 or 3, corresponding to heights of 7, 14 or 21 meters, respectively, as presented in Figure 4.

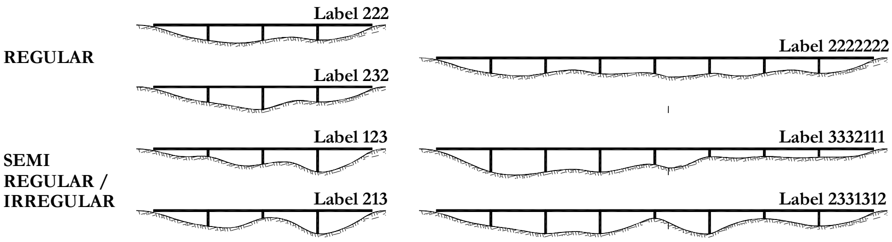


Figure 4 Considered bridge configurations (Casarotti et al., 2005)

The employed set of seismic excitation, used in the nonlinear static procedure, is defined by an ensemble of ten records selected from a suite of historical earthquakes scaled to match the 10% probability of exceedance in 50 years (475 years return period) uniform hazard spectrum for Los Angeles (SAC Joint Venture, 1997), which corresponds, in the current endeavor, to the intensity level 1.0. Additional intensity levels, linearly proportional to the latter by a factor of 0.5, 0.75, 1.5, 3.0 and 3.5, were also considered, thus allowing an overview on how results evolve with increasing seismic intensity. The ground motions were obtained from California earthquakes with a magnitude range of 6-7.3 recorded on firm ground at distances of 13-30 km; their significant duration (Bommer and Martinez-Pereira, 1999) ranges from 5 to 25 seconds, whilst the PGA (for intensity 1) varies from 0.23 to 0.99g, which effectively implies a minimum of 0.11g (when intensity level is 0.5) and a maximum of 3.5g (when intensity level is 3.5). The demand spectrum was defined as the median response spectrum of the ten records. Pushover analyses for plastic hinge models were carried out using SAP2000, whereas for fiber based models analyses, SeismoStruct has been used.

4. RESULTS

4.1. Pushover curves

The NSP application was carried out according to what is suggested in EC8, which makes use of N2 method. According to that, two load shapes have been considered: uniform, named ***uniform***, and first mode proportional, named ***modal***. Moreover, within the NSP application, the reference node is recommended to be taken as the central one, named ***central***. Additionally, for irregular not symmetric configurations, the possibility of choosing the maximum modal displacement as reference node, named ***max***, has also been considered.

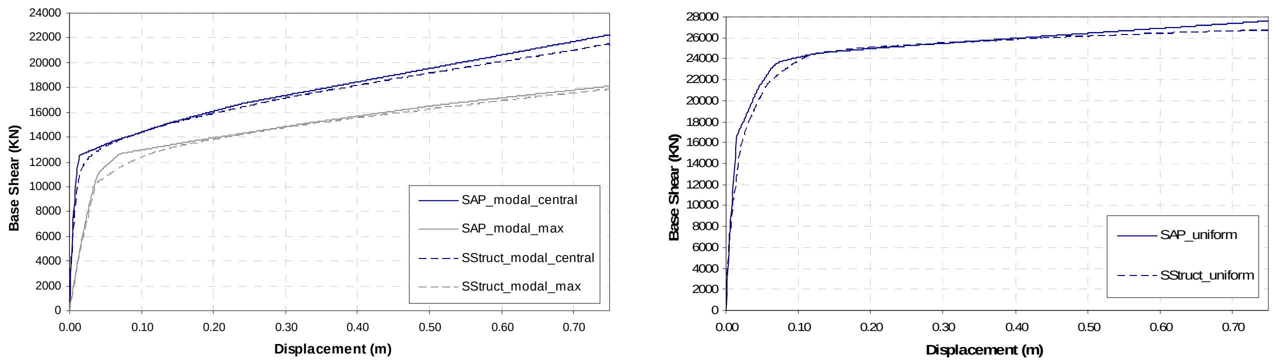


Figure 5 Capacity curves for short irregular bridge (213)

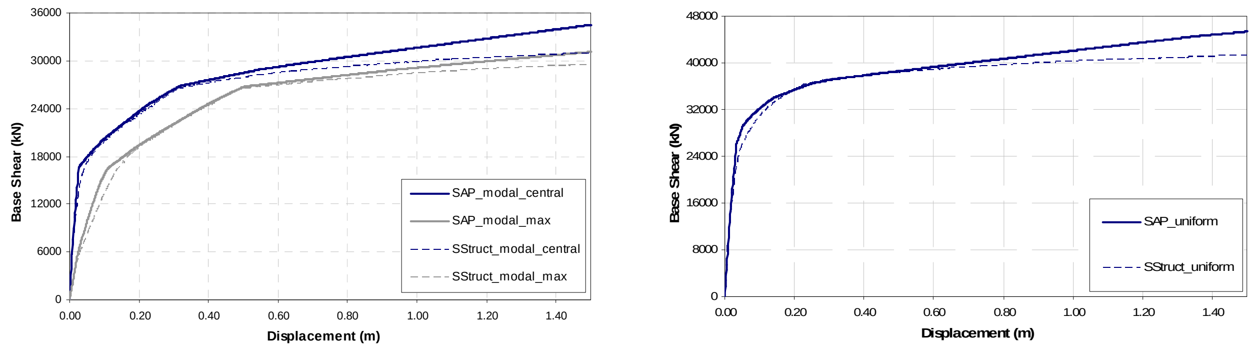


Figure 6 Capacity curves for long irregular bridge (2331312)

Figures 5 and 6 show the capacity curves computed for two irregular configurations, a short and a long one. Results show that differences in the capacity curve are not significant regardless the modeling option for plastic hinges or fiber elements. Slightly less matching results seem to occur for the long bridges, mainly for increasing inelasticity levels. As for the load pattern, no relevant differences are observed: the behavior in both cases is actually quite similar. However, a closer match between the two modeling techniques is attained if the maximum modal displacement is used as reference node. For the rest of the configurations, the results, which are not presented for the sake of simplicity, confirm the observations just made.

4.2. Nonlinear Static Procedure results

The differences in the capacity curve, coming from the pushover analysis, will surely, to some extent, influence the NSP predictions. To compare the NSP predictions coming from different modeling possibilities, the ratio, $\overline{\Delta}_i$, for different evaluation parameters (deck displacements and bending moments and piers/abutments shear forces), is computed at each significant location *i*, considered to be at the piers or the abutments, according to Eqn. 4.1, which is written for a generalized parameter Δ.

$$\overline{\Delta}_i = \frac{\Delta_{i,Push\ SAP}}{\Delta_{i,Push\ SStruct}} \tag{4.1}$$

Furthermore, a single index per bridge, able to tell whether the agreement of the modeling possibilities is good or not, the Bridge Index, BI, based on the original concept from the work of Casarotti and Pinho (2006), was herein defined as the mean of the ratios across all the locations, for each intensity level. Using Bridge Indexes it is possible to look at results in terms of evolution with intensity level.
In Figure 7, BI results are presented for deck displacements and two representative bridge configurations, the same used in the pushover curves comparison.

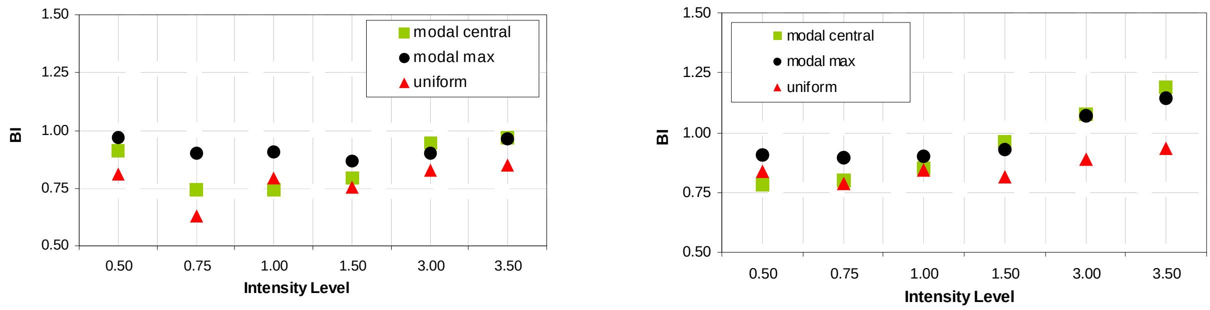


Figure 7 BI for displacements with intensity level for short bridge (213), left, and long bridge (2331312), right

Generally, close to unit ratios are obtained, ranging from 0.8 to 1.2, approximately, for the modal max case, the best performing one. For the long bridge, the agreement of the two modeling possibilities increases with the inelasticity level. First mode proportional load shape leads to better agreement between plastic hinges and fiber elements approaches than uniform loading and the use of the maximum modal displacement as reference node seems to be associated to more coherent results. Furthermore, it is important to notice that irregular bridges are being shown, which are supposed to be critical cases within the application of such nonlinear simplified procedures. This stands for the stability of the NSP, even with not regular structures.
If the median of the BIs is computed for all intensity levels, for every studied bridge, a structural configuration level of results may be obtained, as presented in Figures 8 and 9, where only the maximum modal reference node has been included, given that better results have been obtained for that case.

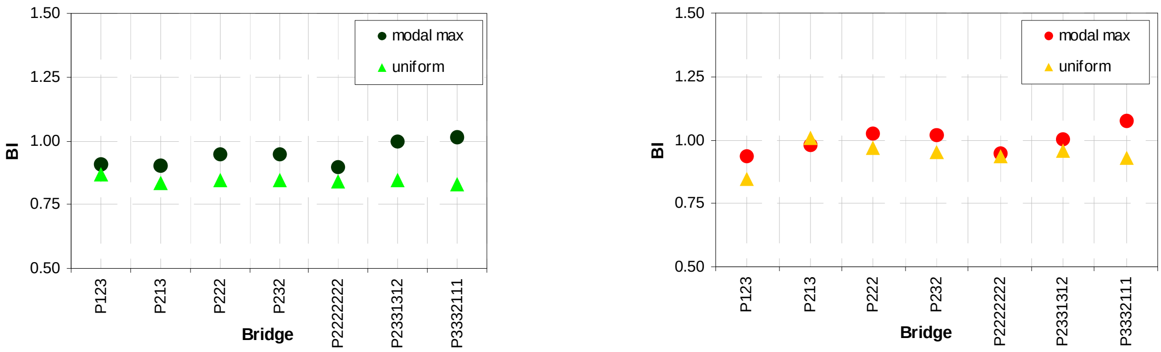
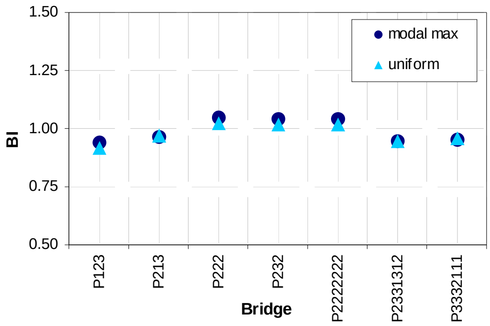


Figure 8 Median BI per bridge configuration: deck displacements (left) and bending moments (right)



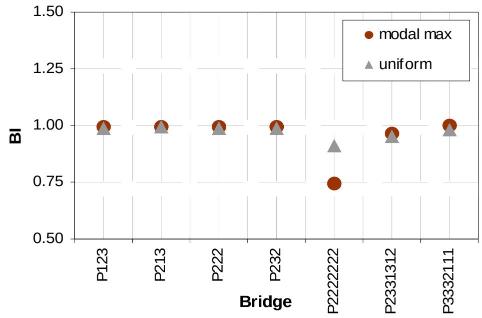


Figure 9 Median BI per bridge configuration: piers (left) and abutments (right) shear forces

There seems to be no clear trend between the structural configuration and quality of agreement in results. What can be seen is that displacement predictions differ more from plastic hinge models to fiber-based ones than the rest of the parameters, since those indexes are the farer to unit ones. The use of the 1st mode proportional load shape is confirmed to yield more consistent results, mainly for deck displacements and bending moments. On the other hand, shear forces, either at the piers or abutments seem to be unaffected by the load shape of the pushover analysis. Displacements and abutment shears seem to be lower according to the plastic hinge model estimates, with the opposite occurring for some cases in deck bending moments and pier shears. Nevertheless, quite good median values, close to one in the majority of the configurations and parameters, are obtained which indicates that there is no clear advantage in using one of the modeling possibilities instead of the other.

4. CONCLUSIONS

The use of different modeling possibilities, plastic hinge models or fiber-based models, within the pushover-based seismic analysis of bridge structures has been studied. The employed analysis method has been the Nonlinear Static Procedure recommended by Eurocode 8 and a set of seven different bridges, including short/long, regular/irregular configurations, has been used in a parametric study evaluating deck displacements and bending moments and pier/abutments shear forces results. Seismic action has been equally widely defined through ten real earthquake records. The following concluding remarks can be made:

- An initial calibration study on the plastic hinge model assumptions has been carried out, pointing out that variables such as plastic hinge length or location do not majorly influence the results in terms of pushover curve. Additionally, it has been verified that inelastic behavior for the piers cross section (moment-curvature trends) was similarly assumed by both models.
- Concerning the direct comparison of pushover curves, it has been seen that larger differences are found in initial cracked elastic behavior, although not significant, whereas maximum forces and yielding deformation are quite similar in both cases.
- Regarding the response parameters, results have shown that, globally, both modeling possibilities had results in quite fair agreement, mainly for higher intensity levels. Only for lower intensity levels some disagreement was found. These differences were found to be due to the NSP base concept of bilinearizing the pushover curve for the performance point, which, for low intensities, will suffer in a larger way, with the coinciding differences in the pushover curves. Generally it can be said that plastic hinge models are associated to lower predictions in deck displacements and abutment shear and higher estimates for deck bending moments and piers shear forces than fiber-based models. Furthermore, within the NSP application, the uniform load pattern lead to less agreeing results.

Summing up, the developed work proved that no major advantages are found when choosing a distributed plasticity model, instead of a concentrated one. To the latter may be pointed out that more assumptions have to be made, such as plastic hinge length or location, even though it has also been seen the low influence on those parameters in such of model type. In the end, the option will have to be made taking into consideration additional aspects, such as computational effort and consumed time or even personal preference of the practitioner.

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