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Evaluation of h, p and hp FEM for Elastostatic Plane Problems

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Abstract

Finite element method (FEM) has become indispensable for numerical simulation in engineering field, especially pure displacement based FEM seems to be conforming in many aspects, such as well-known and easily adaptable method to any other complex analysis like transient and nonlinear ones. This paper firstly gives some impression about production of "p-method" constructed from Lagrange polynomial, Serendipity form and Lagrange and Legendre polynomial based hierarchical forms. Secondly, the performances of "p-method", "h-method", and "hp-method" are discussed on displacement and stress scores in point of degree of freedom when an elastostatic rectangular plane problem with half circle notches is considered. By the way, Blending function method is performed to exactly represent real geometrical curve boundaries. The analyses are performed by a research oriented finite element program developed in MATLAB and the obtained solutions are verified by ANSYS solutions.

Keywords: *"p-method", "h-method", "hp-method", blending function method, elastostatic plane problem.*

1 Introduction

In the conventional finite element method (FEM), general and first way to get admissible solution is to refine mesh until convergence is obtained, which is called as "h-method". Second one in the literature (Szabó and Babuška, 1991; Zienkiewicz and Taylor, 1989) is that representation of displacement fields is made by high-order polynomials, which is known as "p-method". These approaches bring together with some disadvantages. For example, the "h-method" needs more elements and is time-consuming. Also the "p-method"

seems doubtful about its contribution to efficiency of FEM when compared to the classical h-method. In this point, the third approach appears. It is “hp-method”, which is the combination of refining the mesh and increasing the polynomial order. The construction of p-method based on Lagrange polynomial, Serendipity form and Lagrange and Legendre based hierarchic forms has been presented in the previous paper (Bekiroğlu and Kuhl, 2006).

In the concept of this paper, all these methods are implemented on one example by showing improvements of the research oriented code in MATLAB in the previous study. The ability of study with high polynomial degree in the code is improved up to any specified polynomial degree and in order to show this ability polynomial degree is mostly selected as 14. In addition, the code is improved by Blending function method (Gordon and Hall, 1973; Gordon and Hall, 1973; Watkins, 1974; Szabó and Babuška, 1991) since a problem with any curve boundaries is able to be solved, and this improvement is showed in the notched plane problem. Overcoming insufficiency of memory, Frontal Solver (Hinton and Owen, 1977; McGuire et al., 2000) is also adapted to the code. Advantage of this adoption is seen when mesh size is decreased.

2 Numerical Examples

The constructed shape functions are illustrated over an elastosatic plane problem. The considered problem is a rectangular plane having half-circle notches at its upper and lower edges and is subjected to uniform distributed load along its left edge. That the problem has non-linear boundaries implies to absolutely represent its geometrical field in order to get convergence. With the help of blending function method, the geometrical representation is, therefore, made as in its real boundaries. The blending function method is also more useful when p-method is used. Since p-method do not require mesh refinement and is applied to current mesh, to reduce error in representation of geometric field is not possible. So, this disability affects convergence of p-method in negative way. When a shape function based on hierarchic form is used, the negative effect is especially seen in such a way that this situation was illustrated in the previous study (Bekiroğlu and Kuhl, 2006).

The non-linear boundaries cause not only the convergence issue but also stress concentration. For that reason it is why this kind of problem is so useful to test the FEM based on displacement in order to see whatever satisfactory results of stress and displacement is able to be obtained.

2.1 A Rectangular Plane Problem with Half-Circle Notches

Load and restraint conditions and definition of a rectangular plane problem with half-circle notches is given in Figure 1. The problem is modeled by 7 different mesh sizes and for each mesh sizes polynomial degree is increased to 14 except for last two mesh sizes so that for one before the last polynomial degree are 10 and for the last it is 6. Moreover, 4 different aforementioned shape functions are

considered. So, contributions of mesh refinement (h-method), refinement of polynomial degree (p-method) and both of them to speed of convergence are illustrated via each aforementioned shape functions. The mesh refinements are given in Figure 2.

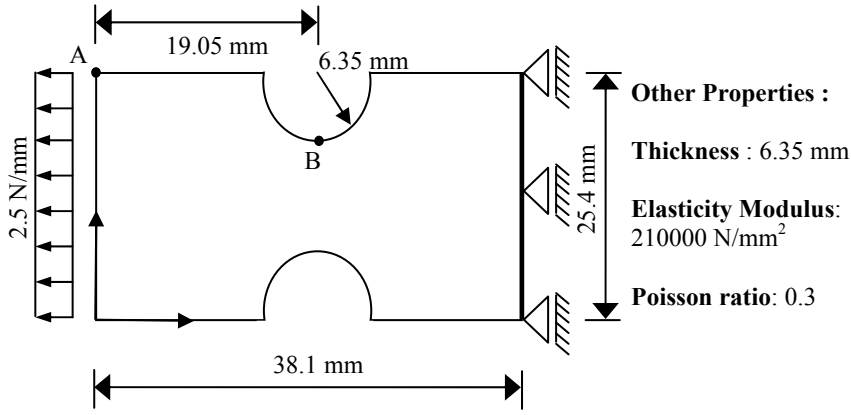


Figure 1. A rectangular plane problem with half circle notches.

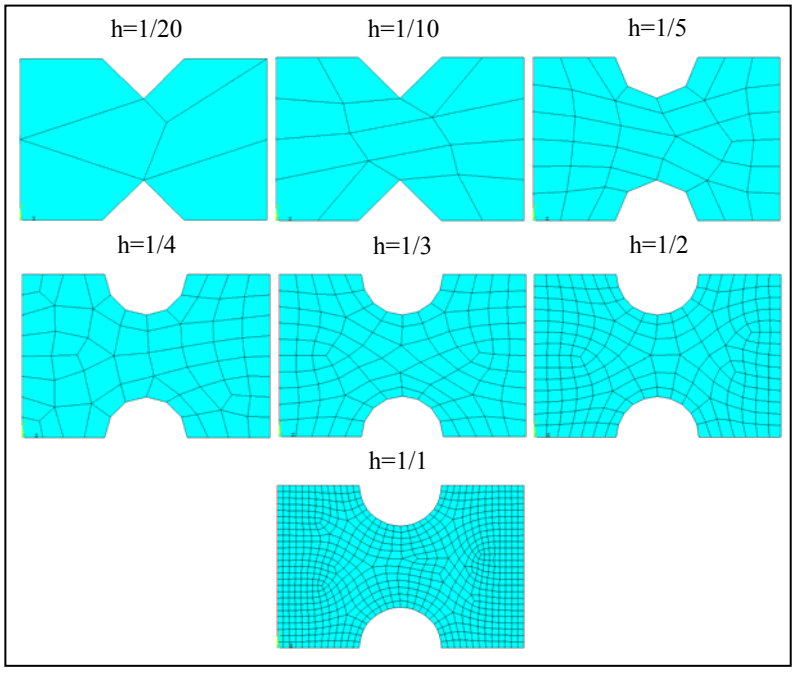


Figure 2. The considered seven mesh refinements.

Firstly, maximum horizontal displacement under the load is given in Figure 3 so as to see convergence behavior of displacement when p-method is considered for each mesh. The displacement forms at point A shown in Figure 1.

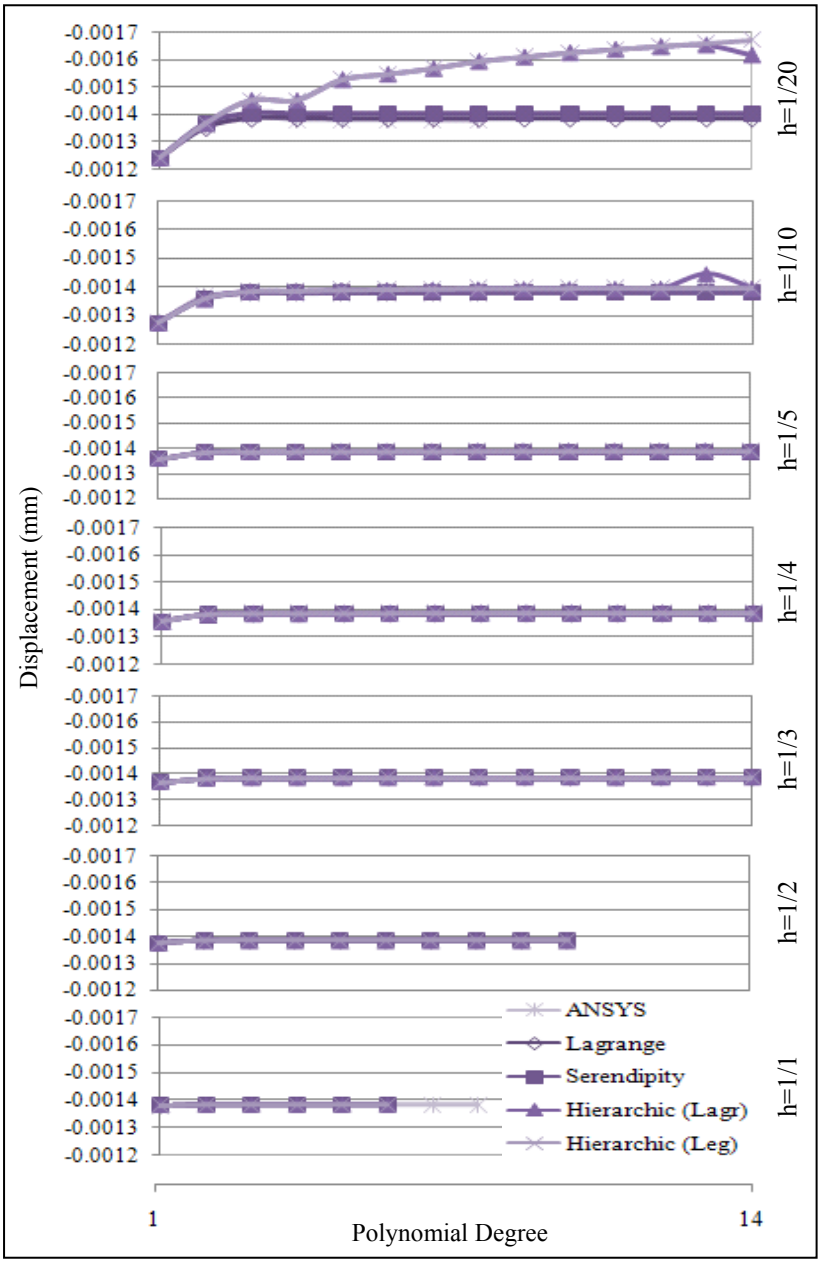


Figure 3. Displacement with respect to polynomial degree and mesh size.

The displacement for h=1/20 converges the exact displacement immediately except for hierarchic form. As in h=1/10, it for Lagrange polynomial based hierarchic form is still able to fluctuate toward high polynomial degree. However, from h=1/5 all the considered shape functions give reliable behavior in convergence. Secondly, the maximum normal stress that is seen at point B is given in Figure 4 with respect to polynomial degree and mesh size.

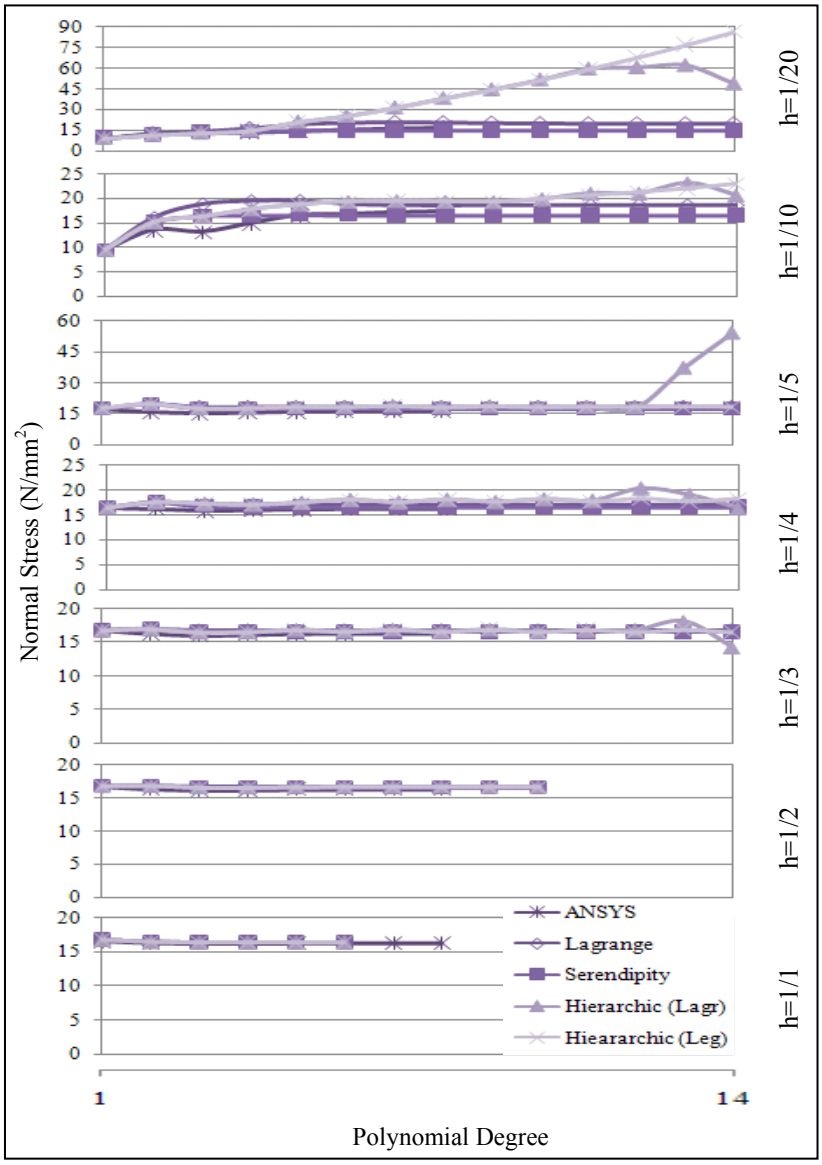


Figure 4. Normal stress with respect to polynomial degree and mesh size.

Before interpretation of stress graphs, it should be said that to get satisfied result in stress field is more difficult than that in displacement field since stress is obtained from displacement with a second operation in displacement based finite element method. So a late satisfaction in stress field is supposed to occur. Looking into Figure 4, for h=1/20 all shape functions except for those in hierarchic form follow a curve of convergence. The behaviors of hierarchic forms, especially that of Lagrange based hierarchic form, seem to be non-converged toward high degree in such a way that this non-converged behavior tends to be disappeared when mesh size is increased. After h=1/10, this is clearly seen for Lagrange based hierarchic form. If a generalization on reliable uses of the considered shape functions based finite elements is made, it is straightforward that all those for stress are reliable up to polynomial degree 10 and the most of those for stress are reliable for every polynomial degree. Thirdly, degree of freedom with respect to polynomial degree for every mesh is given in Figure 5.

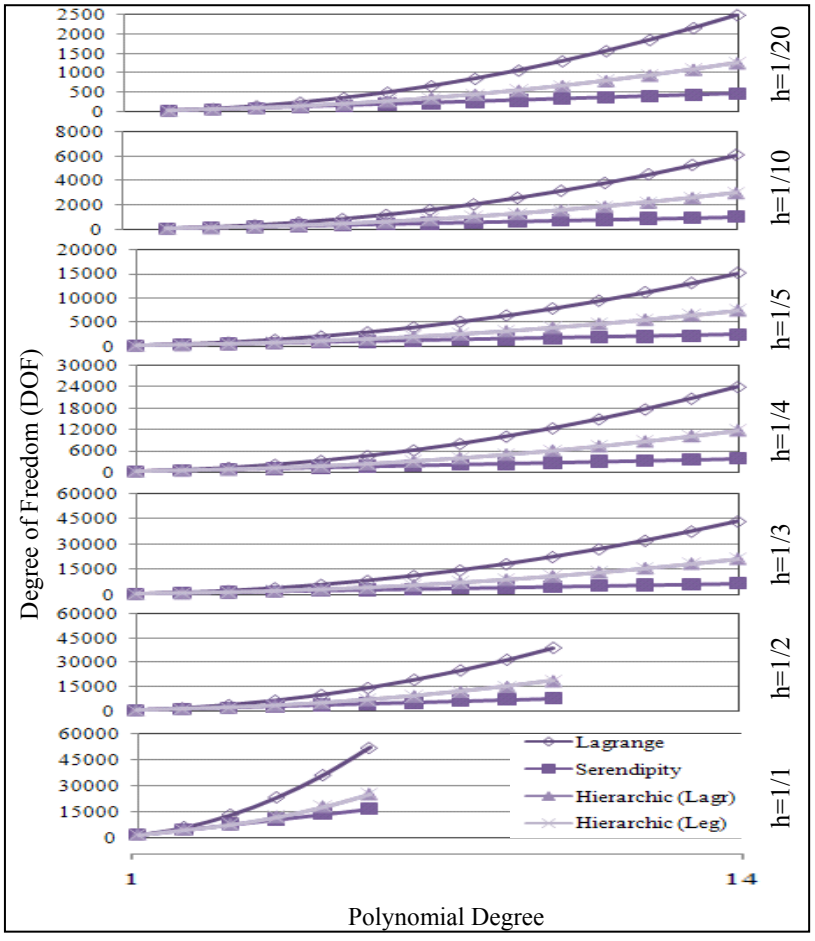


Figure 5. Degree of freedom with respect to polynomial degree and mesh size.

As looked into Figure 5, increment speed of degree of freedom is highest for Lagrange based shape function and is least for Serendipity based shape function. The both hierarchic forms are moderate. If it is more closely looked into Figure 3, 4, and 5, it is seen that to get reliable (i.e. converged) displacement and stress within very well converged value is quite expensive, regarding of degree of freedom, when only h method or only p method is used. In order to more clearly show means with examples, Table 1 and 2 are given below. The values of considered displacement and stress in Table 2 are selected among corresponding converged values through the process at which p method is operated.

Table 1. Displacements, stresses, and degrees of freedom for h-method.

h	p	Displacement (mm)	Stress (N/mm^2)	DOF
1/20	1	-0.0012414	9.3255990	23
1/10	1	-0.0012738	9.4588690	47
1/5	1	-0.0013564	17.5720800	103
1/4	1	-0.0013563	16.5380600	157
1/3	1	-0.0013689	16.7663200	267
1/2	1	-0.0013753	16.7455100	445
1	1	-0.0013816	16.7636700	1545

Table 2. Displacements, stresses, and degrees of freedom for hp-method.

H	p	Displacement (mm)	Stress (N/mm^2)	DOF	CPU time* (sn)	Shape function type
1/20	3	-0.0013848	14.4496500	139	0.53	Lagrange
1/3	3	-0.0013845	16.8047000	2119	19.68	Lagrange
1/2	3	-0.0013845	16.6332700	3625	58.02	Lagrange
1	3	-0.0013845	16.3724000	13189	615.68	Lagrange
1/10	3	-0.0013821	16.4411000	199	1.15	Serendipity
1/5	4	-0.0013845	16.6482500	985	10.16	Serendipity
1/3	3	-0.0013846	16.5343800	1239	12.27	Serendipity
1/2	5	-0.0013846	16.5178800	3749	103.49	Serendipity
1	3	-0.0013845	16.3353000	7485	275.67	Serendipity
1/3	4	-0.0013858	16.5296300	1945	30.80	Hierarchic (Lagr)
1/2	5	-0.0013848	16.6250400	4895	214.24	Hierarchic (Lagr)
1	3	-0.0013846	16.3368400	7485	290.48	Hierarchic (Lagr)
1/3	4	-0.0013858	16.5296300	1945	30.44	Hierarchic (Leg)
1/2	5	-0.0013848	16.6250400	4895	223.11	Hierarchic (Leg)
1	3	-0.0013846	16.3368400	7485	288.18	Hierarchic (Leg)

*The time spent to assemble the whole stiffness matrix of corresponding model

Table 1 presents displacement and stress according to pure h method. According to h-method both displacement and stress is obtained as 0.0013816 mm and 16.76367 N/mm^2 within 1545 degrees of freedom, respectively. These values are converged values for h method, but don't have as enough sensitivity as the values obtained from p method, and hp method. That is, those are not well converged

values. In Table 2 the first converged displacement, 0.0013848, is getting with 199 degrees of freedom, which is better converged value than that for h method in point of both convergence and degree of freedom. Even if both displacement and stress are considered, with 0.0013845 mm and 16.64825 N/mm^2, whose degree of freedom is 985, p method shows superior performance to h method. Table 2, moreover, presents scores based on hp method in such a way that more converged scores than those of both h method and p method are obtained for hp method with less degree of freedom when especially stress is considered. If an answer is asked for which shape function type saves degree of freedom in hp method, the answer is all the shape function types except for Lagrange based type, which are considered in this paper. In Table 2, CPU time scores are also presented in view of giving some impression on computational efficiency of the improved code in this paper. The analyses has been performed on a computer having properties that are 1.6 GHz, 400 MHz FSB 2 MB L2 cache Intel Pentium M 725 processor CPU; 127 GB HDD; 2x1024 MB DDR; and 4096 MB virtual memory.

3 Conclusions

In this paper; h-method, p-method, and hp-method are illustrated on an elastostatic rectangular plane problem with half circle notches. p-method is produced from four different shape functions which are based on Lagrange polynomial, Serendipity form, and Lagrange and Legendre polynomial based hierarchic forms. The example under uniform distributed load is considered over seven mesh refinement for h method and hp method and is discussed to show performance of these methods over displacement and stress scores, regarding of degree of freedom. The conclusions drawn in this paper are given below:

1. p method requires different threshold mesh refinement for the considered shape function types in order to get reliable displacement and stress. Especially, stress is more sensitive to the required threshold than displacement. If a coarse mesh under threshold is used, non-converged situation in displacement and fluctuations in stress are most likely encountered.
2. To get converged displacement is mostly possible for all methods but to get well converged and sensitive displacement and stress is only possible for p and hp method in point of saving degree of freedom.
3. In point of saving degree of freedom, the shape functions constructed from Serendipity form and Lagrange and Legendre polynomial based hierarchic forms are the most desirable among the considered ones in this paper.
4. Lagrange and Legendre based hierarchic forms have also an advantage which keeps matrix of stiffness in well condition. This advantage can be more important when destructive analysis procedure in point of condition of stiffness matrix, such as nonlinear geometrical analysis, is performed.
5. With the help of blending function method, representation of real geometrical curve boundaries is made possible and so insufficiency about the use of the hierarchical forms on curved boundaries is overcome. Moreover,

in p-method, the blending function method removes the requirement of mesh refinement and so, unchanged mesh is able to be used to get convergence.

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