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Research Article

A finite element study on modal analysis of lightweight pipes

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ABSTRACT

Pipes are mainly used in waste, drain and vent systems as well as transporting various liquids that might be corrosive, flammable, explosives, volatile, reactive, or sometimes hazardous to human health. Though pipes are used at the underground or above ground, all of them are exposed to vibration because of external factors. In this study, we focused on topology optimization of steel and PVC (Polyvinyl Chloride) pipes to get lighter ones which will lead to using less material during manufacturing, less CO_2 emission while transporting them to usage areas by vehicles and easier assembling process. Firstly, new lightweight pipe designs were modeled, and then these novel pipe designs with lattice wall thickness were analyzed by using Ansys finite element program in clamped-free, hinged-hinged, and clamped-clamped boundary conditions to obtain the natural frequencies, mode shapes, and displacement values. Moreover, obtained finite element results for steel and PVC pipes were compared with analytical results calculated by using the equation to check and compare with the finite element results. Finite element results were found similar to analytical results at an acceptable level. The results show that lightweight pipes have similar natural frequency values to the commonly used pipe which has fully solid wall thickness and some significant results about displacement values were attained. Lastly, the effect of pipe material on vibration behaviors of pipes was investigated in depth.

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INTRODUCTION

Pipes are widely used in oil pipeline, natural gas pipeline, water distribution lines, waste, drain, vent systems fields and they are subjected to vibration because of many reasons such as excessive pulsation, mechanical resonance or inadequate supports or support structures, flow-induced, equipment mechanical forces, high-frequency acoustic vibrations generated by relief valves or control valves, pressure pulsations from reciprocating equipment, momentum changes due to sudden valve closure, cavitation caused by vapor bubble collapse and sudden flashing of fluids [1–4]. Besides these reasons mentioned above, the earthquake is

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also one of the factors affecting the vibration of the buried pipes [5]. Moreover, it is reported that propagation of seismic waves in the soil causes two types of deformations; Axial deformation caused by the components that propagate along the pipeline axis and bending deformation generated by the components of the waves that propagate in a direction perpendicular to the longitudinal axis [5]. Furthermore, some construction activities such as blasting, pile driving, and traffic loading like train and vehicle generating vibrations to varying degrees [6,7]. These vibrations are transmitted through the ground in the form of stress waves and if these waves encounter an underground structure such as a pipeline, part of the wave is reflected and part of it is transmitted into the structure. The cyclic nature of these vibrations will induce changes in stress levels in the pipes. This situation can lead to fatigue-related damage such as crack propagation [8]. Besides, as a result of pump plant running, activation of shutoff valves, emergency shutdowns, and external effects during operation of the offshore pipelines, vibration in pipes can occur [9]. To prevent the failures of pipes due to vibration, it is quite important to determine the natural frequency of pipes [10–13]. Hence, lots of researchers conducted many studies about the vibration of structures as well as pipes. Fouzi et al [12], Merzuki et al. [13], Eratlı et al. [14] and Atlıhan and Ergene [15] presented finite element studies on welded thin-walled beam, fiber metal composite laminates and layered composite beam with delamination respectively to obtain mode shapes and natural frequencies of structures. Likewise, Hashimy et al. [16] presented a study on the effect of various fluid densities on vibration characteristics in variable cross-section pipes and they reported that it is crucial to obtain the natural frequency of the pipes to have foresight about the resonance of pipes.

In this study, three different lightened pipes containing innovative cellular structure designs in their wall thickness were compared with a fully solid classical pipe by FEA and analytically in terms of vibration. The two most used pipe materials PVC and steel were assigned during modal analysis and displacement of pipes were obtained as well as mode shapes and natural frequencies under various boundary conditions such as clamped-free, hinged-hinged and clamped-clamped. In case of obtaining benefits of pipes including cellular structure designs in wall thickness in vibration, they can be used instead of fully solid pipes. Hence, less material usage at production and less CO_2 emission while transporting them to usage areas by vehicles and lastly, it will be easier to carry them because of their lightweight while assembly process.

MATERIAL AND METHOD

Firstly, a fully solid pipe model (Figure 1e) with an inner diameter of 64 mm, an outer diameter of 75 mm and length of 1000 mm was designed in AutoCAD designing program and then this pipe model was redesigned in order to obtain lightweight pipes (Figure 1(a)). In the light of minimizing the weight of pipes, some cellular structures were placed into the wall thickness (T) of pipes and three new pipe models have been designed which were shown in Figure 1(b-d). In Figure 1(b), the rib shaped pipe model was exhibited and it includes ribs with rib thickness (t) of 0,59 mm. Besides, the honeycomb pipe model was displayed in Figure 1(c) which contains honeycomb structure with height and length (h = l) of 1.89 mm, rib thickness (t) of 0.59 mm, and rib angle (ϴ) of 30°. Lastly, a hybrid structure was designed with the combination of the first two structures (rib model + honeycomb model) as shown in Figure 1(d).

After designing all pipe models, they were transferred into the Ansys APDL program in Iges format and their areas were used as a cross-section of 2D beams. Then, 2 Node 188 beam element type and linear elastic material properties like elasticity modulus (E) of 210 000 MPa, Poisson's ratio (ν) of 0.3 and density (ρ) of 78×10^{-10} ton/mm^3 for steel material [17] and (E) of 2800 MPa, Poisson's ratio (ν) of 0,388 and density (ρ) of $13{,}8 \times 10^{-10}$ ton/mm^3 for PVC material [18] were assigned and 0.295 mm mesh size (half of the minimum thickness value in models) was preferred to approach to real values as much as possible (Figure 2(a)).

Subsequently, clamped-free, hinged-hinged, and clamped-clamped boundary conditions were applied on steel and PVC pipe models respectively as shown in Figure 2(b-d). Then, modal analysis of all pipes was conducted by using Block Lanczos method for 50 modes in Ansys APDL and mode shapes, natural frequency values and displacement vector sum values were obtained numerically at the end of totally 72 finite element analysis. Furthermore, obtained results from finite element analysis for steel and PVC pipes were compared with the analytical results calculated by using Equation (1) to determine the error between two different solution methods.

The natural frequency values (f_n) of a pipe can be calculated by using Equation (1) [19] given below. E is the elasticity modulus of pipe material (Pa), I is 4th moment of inertia of pipe (m^4) (calculated in Ansys APDL), μ is mass per unit length of pipe (kg/m) (calculated according to infill ratio of pipes) and L is the length of pipe (m) and these values were used while calculating the natural frequency of pipes and tabulated in Table 1. Besides, it should be pointed out that E_s and μ_s demonstrate the elasticity modulus and mass per unit length of steel pipe. Similarly, E_p and μ_p are the elasticity modulus and mass per unit length of PVC pipe. Additionally, C describes a constant value related to boundary conditions of pipe, and change of this value was given in Table 2 with mode shapes.

$$f_n = \frac{1}{2\pi} C \sqrt{\frac{EI}{\mu L^4}} \qquad (1)$$

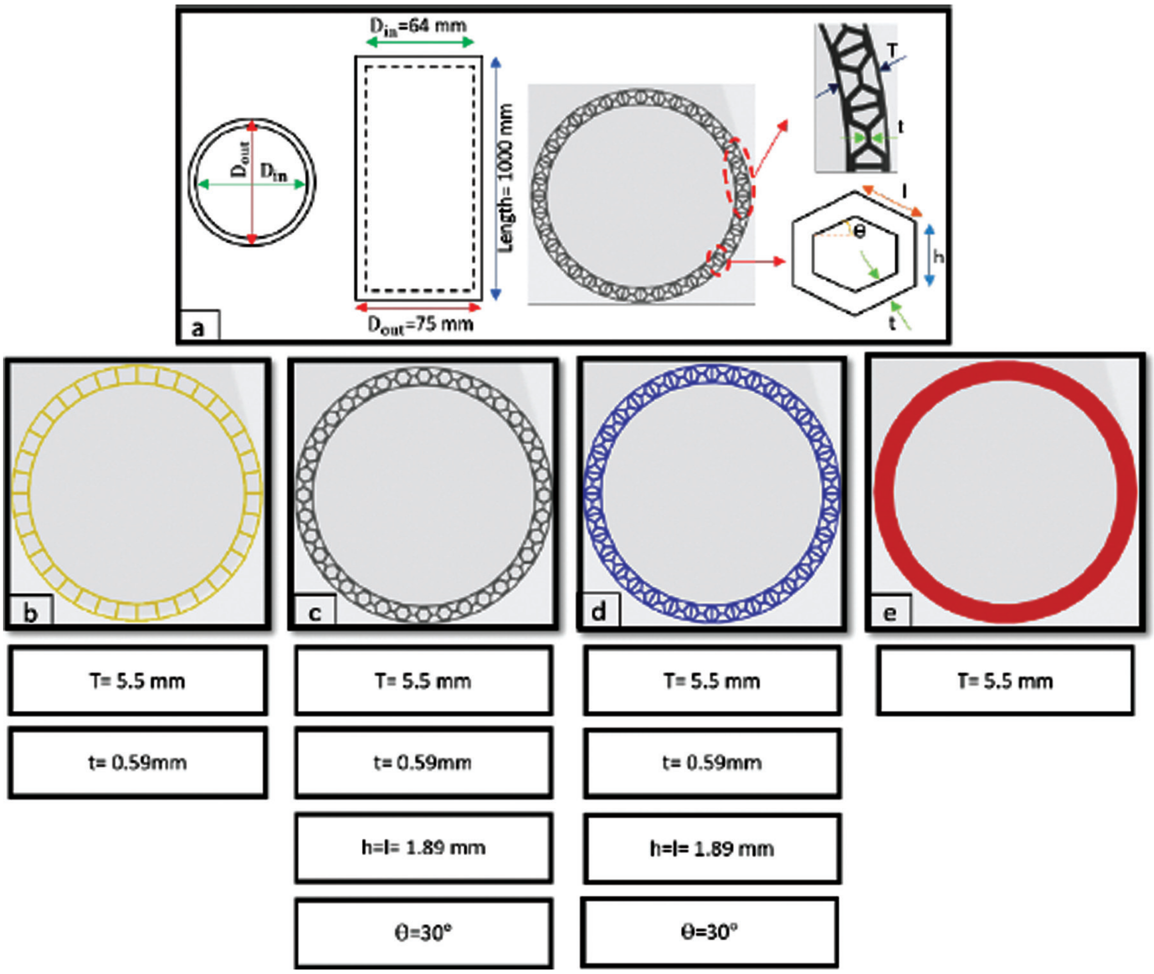


Figure 1. Dimensions and CAD views of designed pipes, a) dimension of pipes, b) rib-shaped pipe, c) honeycomb pipe, d) hybrid pipe, e) fully solid pipe.

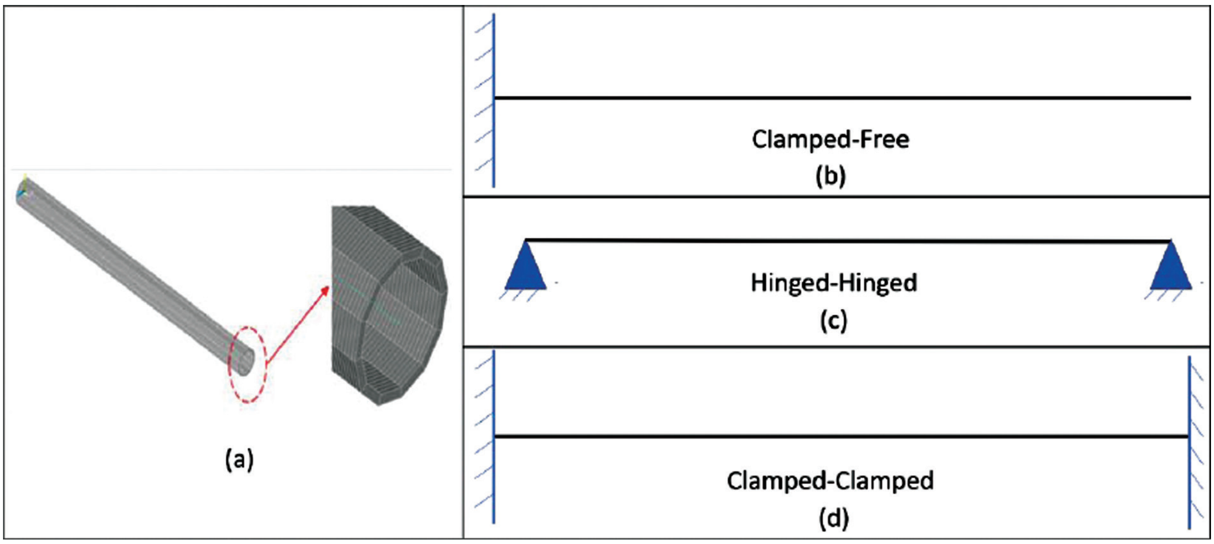


Figure 2. View of mesh and applied boundary conditions on pipes, a) view of mesh, b) clamped-free, c) hinged-hinged, d) clamped-clamped.

Table 1. The values used while calculating the natural frequency of steel and PVC pipes by using Equation (1)

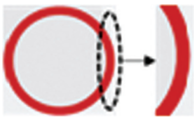
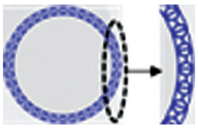
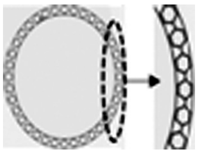
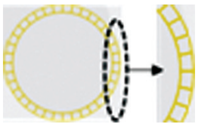
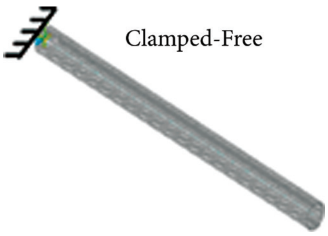
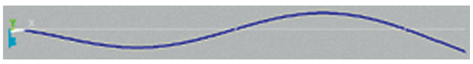
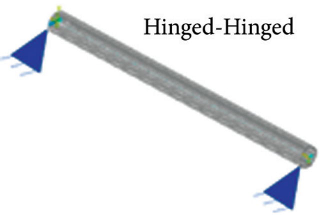
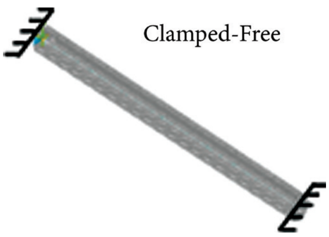
Model shape	E_s (Pa)	E_p (Pa)	I (m^4)	μ_s (kg/m)	μ_p (kg/m)	L (m)
 Fully Solid Pipe	210×10^9	$2,8 \times 10^9$	729236×10^{-12}	9,36	1,656	1
 Hybrid Pipe	210×10^9	$2,8 \times 10^9$	369630×10^{-12}	4,731	0,837	1
 Honeycomb Pipe	210×10^9	$2,8 \times 10^9$	359980×10^{-12}	4,611	0,815	1
 Rib Pipe	210×10^9	$2,8 \times 10^9$	191230×10^{-12}	2,438	0,431	1

Table 2. Boundary conditions, mode shapes, and C constant values for these modes

Boundary Condition Shape	Mode Number	C value	Mode shape
 Clamped-Free	1	3,52	
	2	22,4	
	3	61,7	
 Hinged-Hinged	1	9,87	
	2	39,5	
	3	88,9	
 Clamped-Free	1	22,4	
	2	61,7	
	3	121	

According to Table 2, C constant value of 3,52 for mode 1, C constant value of 22,4 for mode 2, and C constant value of 61,7 for mode 3 should be chosen when clamped-free boundary condition is applied. C constant values of 9,87, 39,5, and 88,9 might be used for mode 1, mode 2, and mode 3 respectively in the hinged-hinged boundary condition.

Lastly, for clamped-clamped boundary condition, C of 22,4 for mode 1, C of 61,7 for mode 2, and C of 121 for mode 3 can be used while calculating the natural frequency values

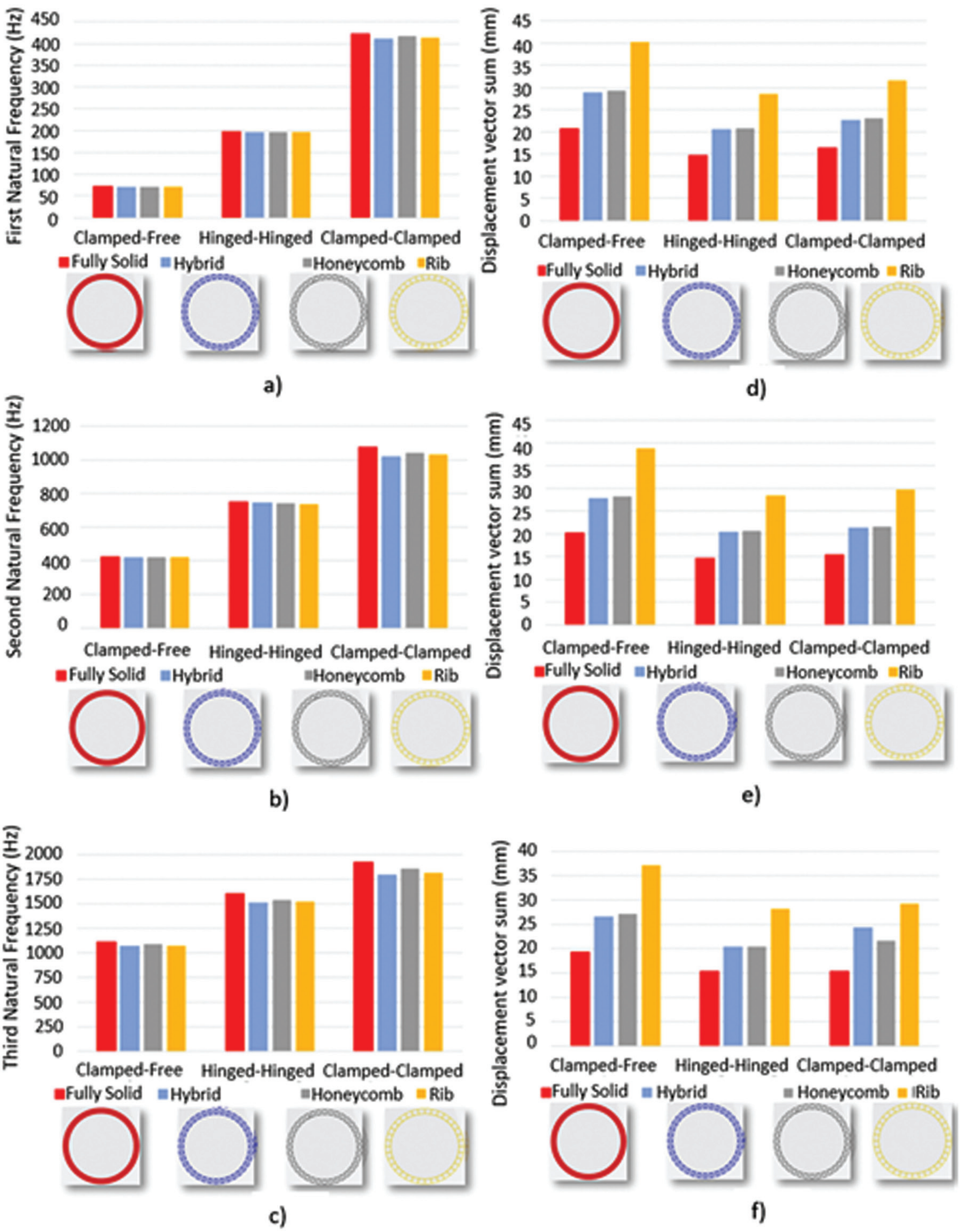


Figure 3. Natural frequency and displacement vector sum values of steel pipe for the first three modes.

by using Equation (1) mentioned above. Moreover, it can be emphasized that mode shapes in clamped-free boundary condition differ from other boundary conditions.

RESULTS AND DISCUSSION

By using Equation (1), the natural frequency values of designed pipes were calculated analytically. Besides, modal analysis results obtained from FEA were tabulated in Table 3 for steel pipes and in Table 4 for PVC pipes. Hence, analytical natural frequency results and 2D FEA natural frequency results of all pipes made from steel and PVC materials were compared for three modes at each boundary conditions such as clamped-free, hinged-hinged, and clamped-clamped. Furthermore, the amount of % error was calculated after comparing analytical and 2D FEA results,

Table 3. Natural frequency and displacement values of steel pipe

Shape of Pipe	Boundary Conditions	Mode numbers	Analytical Natural Frequency Results (Hz)	2D FEA Natural Frequency Results (Hz)	Error (%)	Displacement of vector sum (mm)
Fully Solid	Clamped-Free	Mode 1	71,69	71,01	0,948	20,688
		Mode 2	456,20	423,98	7,062	20,091
		Mode 3	1256,61	1109,50	11,658	19,322
	Hinged-Hinged	Mode 1	201,01	197,46	1,766	14,658
		Mode 2	804,44	751,57	6,572	14,561
		Mode 3	1810,49	1608,97	11,132	15,315
	Clamped-Clamped	Mode 1	456,20	422,82	7,316	16,263
		Mode 2	1256,61	1075	14,452	15,282
		Mode 3	2464,34	1929,60	21,820	15,315
Hybrid	Clamped-Free	Mode 1	71,79	70,823	1,346	28,889
		Mode 2	456,88	415,90	8,969	27,845
		Mode 3	1258,46	1067,15	15,205	26,612
	Hinged-Hinged	Mode 1	201,31	196,29	2,493	20,502
		Mode 2	805,66	734,83	8,791	20,383
		Mode 3	1813,25	1508,11	16,828	20,277
	Clamped-Clamped	Mode 1	456,88	410,99	10,044	22,645
		Mode 2	1258,46	1020,3	18,924	21,279
		Mode 3	2467,98	1794,91	27,272	21,401
Honeycomb	Clamped-Free	Mode 1	71,76	70,91	1,184	29,284
		Mode 2	456,70	419,80	8.079	28,329
		Mode 3	1257,97	1087,35	13,563	27,154
	Hinged-Hinged	Mode 1	201,23	196,85	2.176	20,766
		Mode 2	805,34	742,91	7,752	20,637
		Mode 3	1812,54	1539,81	15,046	20,513
	Clamped-Clamped	Mode 1	456,70	416,68	8,762	22,986
		Mode 2	1257,97	1046,21	16,833	21,598
		Mode 3	2467,02	1857,61	24,702	21,685
Rib	Clamped-Free	Mode 1	71,93	71	1,292	40,252
		Mode 2	457,78	418,19	8,648	38,848
		Mode 3	1260,94	1076,7	14,611	37,165
	Hinged-Hinged	Mode 1	201,71	196,90	2,384	28,558
		Mode 2	807,249	739,30	8,417	28,386
		Mode 3	1816,82	1522,70	16,188	28,230
	Clamped-Clamped	Mode 1	457,78	413	9,781	31,567
		Mode 2	1260,94	1031,80	18,172	29,662
		Mode 3	2472,84	1821,22	26,351	29,814

and % error was found at an acceptable level. For all models, minimum error and maximum error were observed in clamped free and clamped-clamped boundary conditions respectively. Additionally, the % error increased when the mode number increased too.

In Figure 3, natural frequency and displacement vector sum values of steel pipe for the first three modes were shown. It can be commented that all pipe models have quite similar natural frequency values for first natural frequency in the same boundary conditions and these values are approximately 70 Hz for clamped-free, 197 Hz for hinged-hinged and 420 Hz for clamped-clamped boundary conditions (Figure 3(a)). Besides, the boundary condition type has a significant effect on the natural frequency values of all

Table 4. Natural frequency and displacement values of PVC pipe

Shape of Pipe	Boundary Conditions	Mode numbers	Analytical Natural Frequency Results (Hz)	2D FEA Natural Frequency Results (Hz)	Error (%)	Displacement of vector sum (mm)
Fully Solid	Clamped-Free	Mode 1	19,681	19,485	0,995	49,173
		Mode 2	125,242	116,035	7,351	47,697
		Mode 3	344,974	302,697	12,255	45,825
	Hinged-Hinged	Mode 1	55,187	54,153	1,873	34,850
		Mode 2	220,860	205,586	6,915	34,624
		Mode 3	497,075	429,284	13,637	34,391
	Clamped-Clamped	Mode 1	125,242	115,553	7,736	38,638
		Mode 2	344,974	292,665	15,163	36,306
		Mode 3	676,559	523,512	22,621	36,408
Hybrid	Clamped-Free	Mode 1	19,709	19,431	1,410	68,658
		Mode 2	125,425	113,69	9,356	66,072
		Mode 3	345,480	290,549	15,899	63,072
	Hinged-Hinged	Mode 1	55,266	53,810	2,634	48,745
		Mode 2	221,174	200,733	9,242	48,467
		Mode 3	497,783	410,252	17,584	48,232
	Clamped-Clamped	Mode 1	125,425	112,137	10,594	53,787
		Mode 2	345,480	277,059	19,804	50,547
		Mode 3	677,522	485,583	28,329	50,866
Honeycomb	Clamped-Free	Mode 1	19,711	19,456	1,293	69,601
		Mode 2	125,436	114,822	8,461	67,238
		Mode 3	345,510	296,335	14,232	64,376
	Hinged-Hinged	Mode 1	55,270	53,974	2,344	49,372
		Mode 2	221,193	203,075	8,191	49,072
		Mode 3	497,825	419,325	15,768	48,792
	Clamped-Clamped	Mode 1	125,436	113,778	9,293	54,604
		Mode 2	345,510	284,431	17,677	51,309
		Mode 3	677,580	503,199	25,735	51,550
Rib	Clamped-Free	Mode 1	19,756	19,480	1,397	95,665
		Mode 2	125,720	114,34	9,051	92,189
		Mode 3	346,293	293,254	15,316	88,094
	Hinged-Hinged	Mode 1	55,395	53,981	2,552	67,896
		Mode 2	221,694	202,004	8,881	67,499
		Mode 3	498,953	414,396	16,946	67,150
	Clamped-Clamped	Mode 1	125,720	112,972	10,139	74,984
		Mode 2	346,293	280,313	19,053	70,462
		Mode 3	679,116	492,93	27,415	70,867

pipes. From large to small natural frequency values can be listed in clamped-clamped, hinged-hinged, and clamped-free lastly.

According to Figure 3(b), the second natural frequency values of all pipes increase from approximately 420 Hz to 1050 Hz when boundary condition changes from clamped-free to clamped-clamped. Also, for hinged-hinged boundary condition around 740 Hz was obtained. Lastly, it can be reported that the third natural frequency values of steel pipes range between 1067 Hz and 1929 Hz related to the

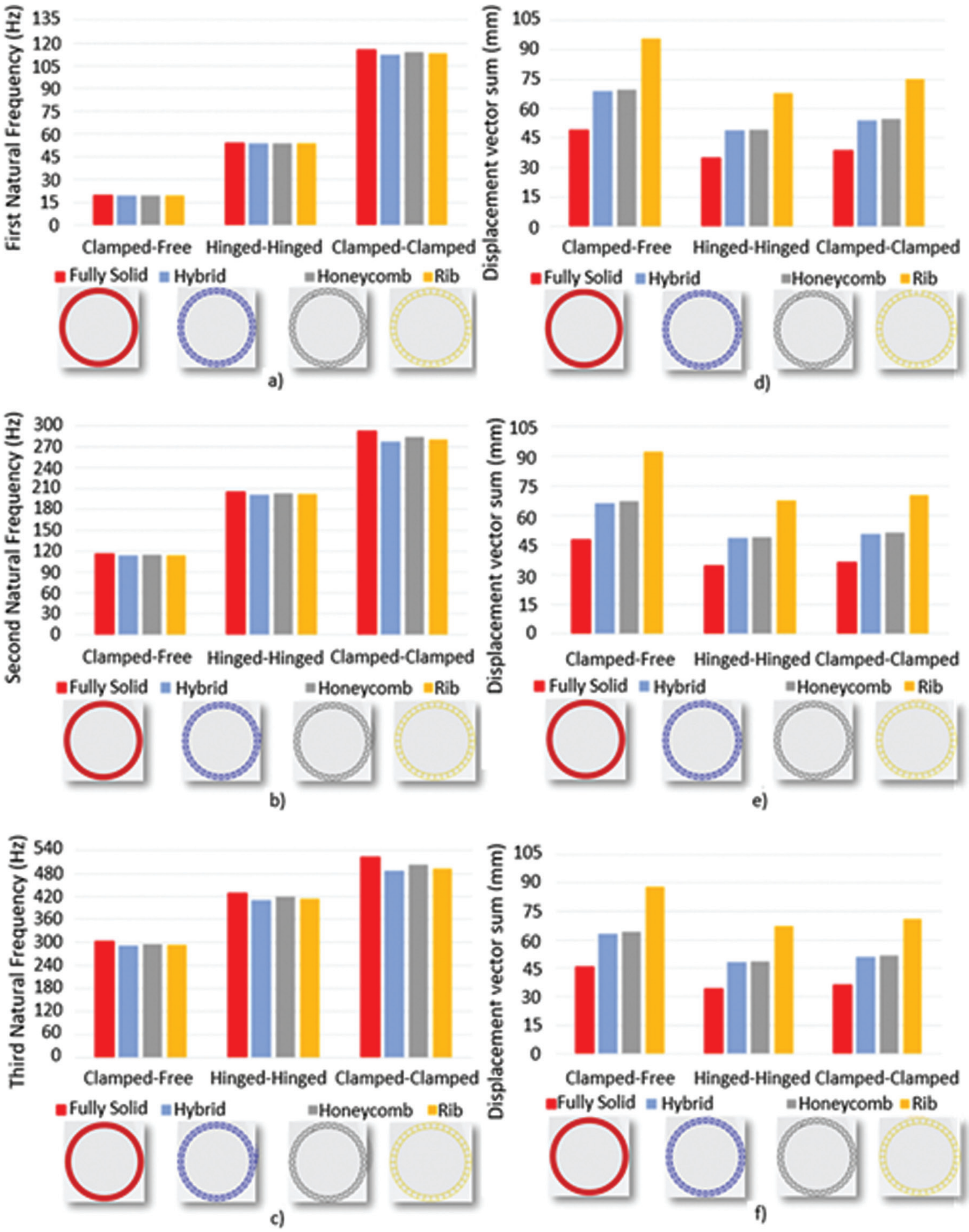


Figure 4. Natural frequency and displacement vector sum values of PVC pipe for the first three modes.

applied boundary condition type. Consequently, the fully solid pipe had the highest natural frequency values for all boundary condition types and its followed by honeycomb pipe, rib pipe, and hybrid pipe respectively.

In Figure 3(d-f), displacement vector sum (resultant displacement) values were presented for the first three modes of steel lightweight pipes. Firstly, the most important result in these figures is that as the filling rate of the pipes decreases, their displacement values mostly increase. However, this situation rarely changes between honeycomb and hybrid structure. When Figure 3(d) is evaluated, rib pipe had the highest displacement of 40,252 mm in clamped-free boundary condition at first mode and its followed by honeycomb pipe with a displacement of 29,284 mm, hybrid pipe with a displacement of 28,889 mm and fully solid pipe with the displacement of 20,688 mm. These results express that design of the pipe can change the resultant displacement of value 2 times though it's length same.

Moreover, another point to be emphasized is that the resultant displacement values of all pipes got the maximum values in the clamped-free boundary condition, and the minimum values were obtained in the hinged-hinged boundary condition. Also, the difference of displacement vector sum values between highest and lowest one decreases when another boundary condition type is chosen instead of a clamped-free boundary condition. Also, when Figure 3(d-e) considered when mode number increased, the huge resultant displacement value difference between rib pipe and others decreases sharply with the decrease of resultant displacement of rib pipe though others have almost the same resultant displacement values.

In Table 4, natural frequency and displacement values of PVC pipe were given similarly to the Table 3 which is valid for steel pipe. Hence, it's possible to compare displacement results, analytically and 2D FEA natural frequency results and lastly % error between analytical and finite element results for PVC pipe as well.

Additionally, in Figure 4, natural frequency and displacement vector sum values of PVC pipes for the first three modes were considered. As an overview, it can be highlighted that PVC and steel materials have the same trend for natural frequency and displacement vector sum values when Figure 3 and Figure 4 compared. However, if PVC material used for pipes, their natural frequency values decrease significantly unlike their displacement vector sum values. Their displacement vector sum values show a great increase.

According to Figure 4(a) for the first modes, all pipes have around 20 Hz natural frequency value for clamped-free, 55 Hz natural frequency value for hinged-hinged and 115 Hz natural frequency value for clamped-clamped boundary conditions. Besides, these values reach to 115 Hz for clamped-free, 205 Hz for hinged-hinged, 285 Hz for clamped-clamped boundary conditions at second mode shape (Figure 4(b)). Lastly, maximum natural frequency values were obtained in the third mode averagely 300 Hz for clamped-free, 420 Hz for hinged-hinged, and 500 Hz for clamped-clamped boundary conditions (Figure 4(c)). Moreover, when the natural frequency values in all modes were examined, the natural frequency of the full solid pipe took the first place and its followed by honeycomb, rib, and hybrid pipes.

In Figure 4(d-f) is evaluated, resultant displacement values change with the boundary conditions. It can be pointed out that minimum and maximum displacement values for all pipes were obtained in hinged-hinged and clamped-free boundary conditions respectively. Besides, resultant displacement values show a decrease when the mode number increasing.

On the other hand, hybrid and honeycomb pipes often exhibit too similar results. Obtained all finite element and analytical results point out that natural frequency values of lightweight pipes are very close to fully solid pipe ranging from 5 mm to 3500 mm diameter is used in many applications for each boundary condition such as clamped-free, hinged-hinged and clamped-clamped. On the other hand, resultant displacement values of pipes change with relating their infill ratio.

CONCLUSION

The following major outcomes were obtained from this study;

- All pipes including novel design pipes such as honeycomb-shaped, rib shaped, and hybrid pipes made of steel were analyzed numerically and analytically. Finite element results and analytical results are in great harmony and the obtained % error amount between these results is at an acceptable level.
- The type of boundary conditions has a significant effect on natural frequency and displacement vector sum values of pipes. Minimum and maximum natural frequency values were obtained in clamped-free and clamped-clamped boundary conditions respectively. The effect of boundary conditions such as the difference of maximum and minimum values diminished when mode number increased.
- Besides unlike natural frequencies, occurred displacement vector sum values took the highest values in clamped-free, and the lowest values in hinged-hinged boundary conditions.
- When the mode number increased, natural frequencies decreased and displacement vector sum values increased.
- The type of pipes did not exhibit a great change in the natural frequency of pipes through the displacement vector sum values that were sharply affected.
- Lastly, material selection for the pipe is critical when natural frequency and displacement vector sum values of pipes are evaluated. For instance, pipes made

of PVC material displaying much lower natural frequency and higher displacement values when compared to pipes made of steel material.

- In conclusion, a suitable die can be designed and additively manufactured for mass production of lightweight PVC pipes and steel pipe manufacturing systems can be optimized to produce lightweight steel pipes which will provide many advantages mentioned earlier.

NOMENCLATURE

2D	Two Dimensional
D_{in}	Inner Diameter, mm
D_{out}	Outer Diameter, mm
E	Elasticity Modulus, MPa
FEA	Finite Element Analysis
f_n	Natural Frequency, Hz
h	Height, mm
I	4^{th} moment of inertia of pipe, m^4
L	Length of the pipe, m
l	Length, mm
PVC	Polyvinyl Chloride
T	Wall Thickness, mm
t	Rib Thickness, mm

Greek symbols

μ	Mass per unit length of pipe
ν	Poisson's ratio
ρ	Density
θ	Rib angle

AUTHORSHIP CONTRIBUTIONS

Concept: B.E., B.Y.; Design: B.E.; Materials: B.E., B.Y.; Data analysis: B.E.; Literature research: B.E.; Writing: B.E.; Critical revision: B.Y., B.E.

DATA AVAILABILITY STATEMENT

No new data were created in this study. The published publication includes all graphics collected or developed during the study.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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