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2D LATTICE STRUCTURES - A PARAMETRIC ANALYSIS.

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Abstract. *As discussed in a number of papers, both the static and the dynamic response of square lattice materials are strongly affected by the inner microstructure. It is worth noting that results obtained without considering this influence are totally misleading, especially if non-uniform changes in terms of stresses and strains are concerned at the local scale.*
Within this context, the present work focuses on a parametric analysis aimed at evaluating the influence of the main mechanical properties of RUC on the dynamic response of a 2D square lattice, thus extending previous results towards the condition of a possible different non-uniform mass density distribution over the RUC configuration.
The existence of the band gaps within the low frequency region is searched as well as the position and width of the existing gaps are evaluated by means of a numerical strategy already developed and tested.

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NOTATION (MINIMAL)

a	lattice constant,
l_1	length of the primary micro-beams,
l_2	length of the auxiliary micro-beams,
A	cross-section area per unit length,
A_s	cross-section shear area per unit length,
I	flexural inertia per unit length,
E	longitudinal normal modulus,
G	shear modulus,
n	Poisson ratio,
l	microscale characteristic length,
ρ	mass density.

1 INTRODUCTION

Beyond the high performances of 2D lattices from a static point of view [1-6], there is a great interest in searching for the existence of band gaps within the low frequency region, which is a key topic for a number of innovative applications. These include energy absorption devices, noise and vibration controllers as well as advanced strategies for the seismic isolation [7-12].

The main preliminary consideration is that the underlying microstructure may influence the mechanical response of 2D square lattice according to a complex interplay between different mechanisms. A first one, which is still under investigation by researchers worldwide, is related to the so-called "size-effect" of the slender members of the RUC. This effect is relevant both on the static and on the dynamic properties. Another mechanism concerns the mass density distribution. It has been demonstrated that lumped masses placed in a non-uniform way over the RUC configuration may facilitate additional band gaps to appear and magnify their width at the same time, thus allowing the 2D square lattice to behave as a mechanical waves filter. In a manner of speaking the final behaviour of a 2D square lattice in presence of a wave signal is influenced not only by the RUC configuration. How the mass distribution is spanned over the RUC seems to be more and more relevant. Moreover, an additional mechanism concerns the inner damping characteristics of the constituent materials, which usually are polymer-based.

From a mechanical perspective, the study of the dynamic properties of a 2D lattice is usually based on several assumptions. Primary, the hypothesis of an infinite lattice is helpful due

to the possibility of restricting the analysis to the representative unit cell (RUC) by virtue of the Bloch theorem.

As an example, a simple configuration of the representative unit cell is shown in Figure 1, where the symbols $\mathbf{a}_1$ and $\mathbf{a}_2$ are for the generating vectors along the directions of spatial periodicity. The considered topology in this case requires that $\mathbf{a}_1$ and $\mathbf{a}_2$ are normal to each other.

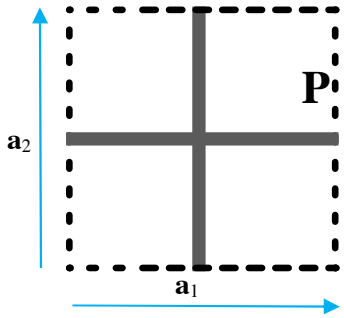

Figure 1. Two-dimensional square lattice material (example of a generic cell).

The displacement of an arbitrary point P of the infinite 2D lattice is given by:

$$\mathbf{u}(\mathbf{r}) = \mathbf{u}_k(\mathbf{r}) \exp(-i\omega t + \mathbf{k}\cdot\mathbf{r}) \tag{1}$$

with the symbol $\mathbf{r}$ indicating the position vector of a generic material point P, the symbol $\mathbf{k}$ denoting the Bloch wave vector, ω the angular frequency and $\boldsymbol{u}_k(\mathbf{r})$ the amplitude which exhibits the same spatial periodicity as the point lattice. It useful to express the position vector $\mathbf{r}$ as follows:

$$\mathbf{r} = \mathbf{r}_0 + n_1\mathbf{a}_1 + n_2\mathbf{a}_2 \tag{2}$$

where (n_1, n_2) is an integer pair and $\mathbf{r}_0$ is the position vector of **O**, which is the corresponding point of **P** within the RUC. Equation (1) becomes:

$$\mathbf{u}(\mathbf{r}) = \mathbf{u}(\mathbf{r}_0) \exp(n_1\mathbf{k}\cdot\mathbf{a}_1 + n_2\mathbf{k}\cdot\mathbf{a}_2) \tag{3}$$

The periodic boundary condition for the dynamic analysis of the unit cell assumes the following final form:

$$\mathbf{u}(\mathbf{r}) = \mathbf{u}(\mathbf{r}_0) \exp\left[2p\,(n_1k_1 + n_2k_2)\right] \tag{4}$$

under the hypothesis the Bloch wave vector is represented by means of a linear combination of the reciprocal space vectors $\mathbf{b}_1$ and $\mathbf{b}_2$:

$$\mathbf{k} = k_1\mathbf{b}_1 + k_2\mathbf{b}_2 \tag{5}$$

2 MECHANICAL MODEL

The mechanical model proposed for the dynamic analysis of 2D lattice materials is discussed in great detail in two previous works [13-14].

The main assumptions are:

- The spatial periodicity vectors $\mathbf{a}_1$ and $\mathbf{a}_2$ are orthogonal to each other with the same norm a. This implies the investigation is limited to square lattice only.
- The RUC configuration can be modelled by interconnecting straight micro-beams.
- The primary microstructure is made of four micro-beams, which are present in any case (Fig. 2.I). Auxiliary micro-beams can be present depending on the designed topology (Fig. 2.II).
- Rigid internal connections are considered.

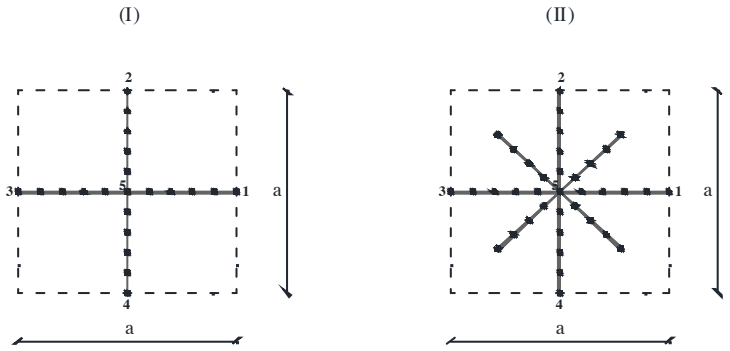

Figure 2. Examples of RUC of a 2D square lattice material (a being the lattice constant).

In the present work, moreover, couple stresses are considered together with classical Cauchy stresses by means of an additional constitutive parameter with the physical dimension of a scale length [15-20]. The scope is to account for the micro-beams local behaviour. It is also important to underline that couple stresses are considered in a simplified manner, according to the so-called Modified Couple Stress Theory, which assumes only the symmetric part of the rotation gradient may influence the strain energy density, as discussed from a critical viewpoint in [21]. Finally, the mass distribution is allowed to be not uniform over the RUC configuration, which is the novel feature of the present work.

3 NUMERICAL ANALYSES

A parametric analysis has been carried out with the aim of underlying the influence of the microstructural behaviour on the dynamic response of a 2D square lattice. Two aspects are considered: the presence of an auxiliary microstructure and/or the presence of the size-effect ($l \neq 0$). Geometric and mechanical characteristics of the reference unit cell are summarized in Table 1.

#	RUC	a	l_1	A	A_s	I	l_2
		[mm]	[mm]	[mm^2/mm]	[mm^2/mm]	[mm^4/mm]	[mm]
1	I	1.0×10^{-1}	5.0×10^{-2}	5.0×10^{-3}	4.17×10^{-3}	1.04×10^{-8}	0.00
2	II	1.0×10^{-1}	5.0×10^{-2}	5.0×10^{-3}	4.17×10^{-3}	1.04×10^{-8}	3.54×10^{-2}

Table 1 Geometry and mechanical parameters (I/II indicating the considered topology as in Fig. 2).

It is worth noting that the considered geometry is the same investigated in [14]. Dealing with the constituent materials, the following hypotheses are taken into consideration:

- The primary micro-structure is composed of aluminium: E=9.00×10^4 N/mm^2; ν=0.23; G=3.66×10^4 N/mm^2; l= 6.58 mm; ρ=2.70×10^{-6} kg/mm^3.
- If an auxiliary micro-structure is present, this one is composed of aluminium (i), as above, or epoxy resin (ii): E=1440 N/mm^2; ν=0.38; G=522 N/mm^2; l=17.6 mm; ρ=1.10×10^{-6} kg/mm^3.

The possibility of considering different materials for the primary and the auxiliary microstructures represents a generalization of the parametric analysis discussed in [14]. Moreover, three different further assumptions are considered:

a) the microscale characteristic length l is equal to zero (i.e. the size effect is discarded);
b) the size effect is present ($l \neq 0$) for the auxiliary beams of the RUC [21-22];
c) the size effect is present for both primary and auxiliary beams of the RUC [21-22].

For what concerns the finite element approximation, a detailed description of the proposed approach is discussed in [13] as well as the "enhanced" finite element proposed for this scope. The convergence rate and the accuracy of the numerical solutions have been adequately assessed in a previous work [14].

4 DISCUSSION AND FINAL REMARKS

In Table 2 the main results concerning the lowest natural frequencies (not dimensional) are presented. They refer to the relevant points **O**, **A** and **B** of the boundary of the irreducible part of the first Brillouin zone indicated in Figure 3.

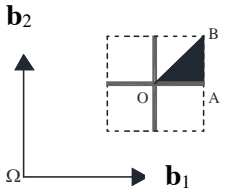

Figure 3. Irreducible part of the first *Brillouin* zone.

The results are presented in terms of dimensionless frequency values which are identified from the eigenvalues and represented as follows:

$$\tilde{w} = w / w_1, \qquad \text{with} \quad w_1 = \frac{\rho}{a^2}\sqrt{\frac{EI}{\rho A}}. \tag{6}$$

		1	2	3	4	5	6	7	8	9	10
1.a	O	0.0	0.0	4.2	4.2	6.1	9.3	18.8	18.8	23.9	29.4
	A	0.8	2.4	3.3	7.0	11.5	13.2	14.5	20.0	25.5	32.9
	B	1.7	2.2	8.9	11.6	11.6	12.7	17.0	17.0	28.9	34.7
1.b	O	0.0	0.0	10.8	10.8	15.9	21.7	37.1	37.1	52.1	56.4
	A	2.0	6.6	7.5	15.9	17.8	25.7	30.4	36.6	51.6	53.2
	B	4.2	5.7	14.1	14.1	22.1	27.4	30.6	30.9	48.2	48.3
2.a.i	O	0.0	0.0	2.6	3.7	4.0	4.3	4.3	4.8	7.9	9.3
	A	0.6	2.2	3.0	3.3	4.2	4.3	4.3	8.4	10.3	11.9
	B	1.5	2.2	3.0	4.2	4.3	4.3	9.7	9.8	10.7	12.7
2.a.ii	O	0.0	0.0	1.1	1.1	1.1	1.1	4.0	4.0	5.8	6.3
	A	0.6	1.1	1.1	1.1	1.2	2.3	3.3	6.2	6.3	6.3
	B	1.0	1.1	1.1	1.1	1.7	2.2	6.1	6.3	6.3	6.3
2.b.i	O	0.0	0.0	2.9	3.8	4.0	9.3	9.6	11.4	11.4	12.4
	A	0.6	2.2	3.3	3.5	8.4	9.5	11.4	11.4	12.7	13.5
	B	1.5	2.2	3.5	8.2	9.8	11.4	11.4	12.6	12.7	12.7
2.b.ii	O	0.0	0.0	1.2	1.2	1.2	1.2	4.0	4.0	6.0	6.9
	A	0.6	1.2	1.2	1.2	1.3	2.3	3.3	6.6	6.8	6.9
	B	1.1	1.2	1.2	1.2	1.7	2.2	6.7	6.8	6.9	6.9
2.c.i	O	0.0	0.0	7.0	9.6	10.2	11.4	11.4	12.7	19.5	21.7
	A	1.5	6.0	6.8	8.0	10.1	11.4	11.4	14.5	20.4	26.4
	B	3.7	5.7	7.7	8.8	11.4	11.4	11.5	13.8	25.0	27.3
2.c.ii	O	0.0	0.0	1.2	1.2	1.2	1.2	6.9	6.9	6.9	7.0
	A	1.2	1.2	1.2	1.2	2.0	6.2	6.8	6.9	6.9	7.1
	B	1.2	1.2	1.2	1.2	4.2	5.7	6.9	6.9	6.9	6.9

Table 2 - First natural frequencies ω_1.

The numerical results presented in Table 2 allow to make a comparison between two different hypotheses concerning the constituent material of the auxiliary microstructure: i) aluminium (i.e. the same material as the primary microstructure) or ii) epoxy resin. Moreover, the comparison is extended to the influence of the microstructure length, according to the assumptions previously summarized by acronyms “a”, “b” and “c”.

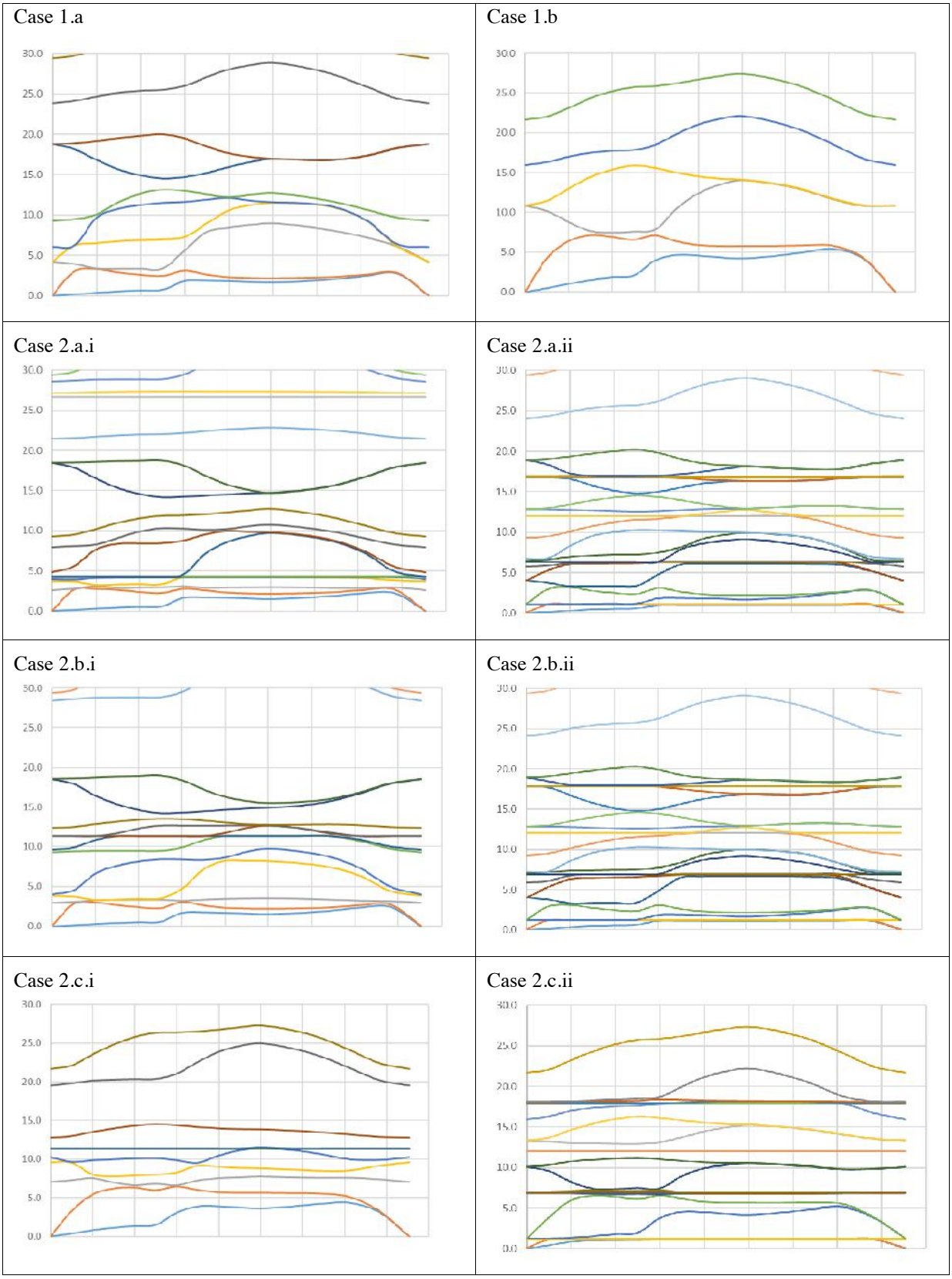

Figure 4. Frequency band structures (not dimensional)

(abscissa lying on the boundary **OABO** of the irreducible part of the first *Brillouin* zone)

In Table 3 the position and the width of the first band gaps are presented. It is also indicated the number corresponding to the immediately below band (lower band number).

		1	2	3	4	5	6	7	8	9	10
position	1.a	3.300	13.860	21.936	29.166	35.260	45.858	66.796	74.461	89.245	105.955
Gap		0.046	1.347	3.856	0.472	1.133	7.388	1.283	0.672	5.260	0.910
# Lower band		2	6	8	9	10	12	16	18	20	22
Position	1.b	7.263	15.914	28.868	42.659	64.808	74.250	91.520	104.320	118.630	156.655
Gap		0.280	0.044	2.999	11.055	5.240	3.774	7.614	8.200	8.280	10.170
# Lower band		2	4	6	8	12	14	16	18	20	26
Position	2.a.i	3.184	13.449	20.105	24.745	26.916	28.006	35.162	45.711	51.342	67.185
Gap		0.115	1.439	2.704	3.840	0.501	1.205	0.942	3.948	7.314	0.505
# Lower band		3	10	12	13	15	16	18	22	24	28
Position	2.a.ii	1.068	1.075	3.240	14.644	16.943	22.136	29.207	35.240	44.295	46.572
Gap		0.001	0.013	0.061	0.213	0.012	3.828	0.390	1.094	4.155	0.049
# Lower band		2	4	6	18	22	24	25	30	36	38
Position	2.b.i	13.871	23.672	35.117	45.266	47.436	49.368	51.656	55.370	77.055	92.386
Gap		0.686	9.455	0.853	3.169	0.499	3.366	0.999	6.430	3.015	10.296
# Lower band		10	12	14	18	19	21	22	24	30	32
Position	2.b.ii	1.205	1.208	3.217	14.685	17.938	22.199	29.246	35.241	44.601	47.199
Gap		0.001	0.006	0.123	0.182	0.053	3.800	0.313	1.096	4.761	0.048
# Lower band		2	4	6	18	22	24	25	30	36	38
Position	2.c.i	6.551	7.743	12.121	17.030	28.808	36.918	44.041	47.837	49.800	51.654
Gap		0.139	0.085	1.228	5.022	3.019	0.571	7.288	0.303	2.460	1.002
# Lower band		2	3	7	8	10	12	14	16	17	18
Position	2.c.ii	1.205	1.225	6.639	7.299	11.587	12.471	28.859	36.909	42.145	47.197
Gap		0.001	0.040	0.115	0.166	0.843	0.925	2.992	0.157	9.421	0.053
# Lower band		2	4	6	10	12	14	22	28	32	34

Table 3 - Position and width for the lowest gaps.

The main conclusions can be summarised as follows. 1. The magnitude of the micro-scale length l influences the position and width of the first band gaps. A forward shift of the first band gaps is determined by the presence of the size-effect. 2. The presence of the auxiliary micro-structure allows flat bands to appear in the low frequency region. 3. A not-uniform dis-

tribution of the mass density over the RUC produces a significant change of the band structure of the 2D lattice.

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