

有限元分析期末作业

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1 简介

我制作了一个使用 C++ 的四面体四节点单元的有限元求解器，可使用自定义的模型，效率较高。处理带有 3446 个节点，12585 个单元的模型仅仅耗时 570ms。

该程序通过在 json 文件中配置单元的材料，节点位置，单元包含的节点序号，位移约束以及节点上的输入力来完成有限元分析计算。该程序通过 json 文件进行结果的输出，其中包括每一个节点的位移量，以及每个单元所受到的应力以及应变。并且通过第四强度理论（应变能理论，即 Von Mises）计算每一个节点的应变能。

$$\sigma = \sqrt{\frac{1}{2}((\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2)} \leq [\sigma]$$

1.1 输入输出文件

输入输出主要通过 json 文件来完成，现通过一个 12 节点的简单网格划分，来解释文件中的参数。

1.1.1 输入文件

```
{  
  "nodes": [      （每个节点的三维坐标）  
    [0, 0, 0],  
    [0, 3, 0],  
    [0, 3, 3],  
    [0, 0, 3],  
    [3, 0, 0],  
    [3, 3, 0],  
    [3, 3, 3],  
    [3, 0, 3],  
    [6, 0, 0],  
    [6, 3, 0],  
    [6, 3, 3],  
    [6, 0, 3]  
  ],  
}
```

```

"elements":[      (单元的序号以及对应的 4 个节点)
    {"number":100, "node":[1,2,3,6]},
    {"number":101, "node":[1,0,3,5]},
    {"number":102, "node":[1,3,5,6]},
    {"number":103, "node":[3,4,6,7]},
    {"number":104, "node":[0,3,4,5]},
    {"number":105, "node":[3,4,5,6]},
    {"number":106, "node":[5,6,7,10]},
    {"number":107, "node":[5,4,7,9]},
    {"number":108, "node":[5,7,9,10]},
    {"number":109, "node":[7,8,10,11]},
    {"number":110, "node":[4,7,8,9]},
    {"number":111, "node":[7,8,9,10]}
],
"constrains":[      (位移约束)
    {"node":0, "displace":[0, 0, 0]},
    {"node":1, "displace":[0, 0, 0]},
    {"node":2, "displace":[0, 0, 0]},
    {"node":3, "displace":[0, 0, 0]}
],
"forces":[      (在节点上施加的力)
    {"node":11, "forceval":[1.0, 1.0, 1.0]}
],
"material":{      (材料的弹性模量和泊松比)
    "modulus-of-elasticity":1e3,
    "poisson-ratio":0.3
}
}

```

1.1.2 输出文件

```

{"elements":[

```

Node 为节点编号, number 为单元的编号, strain 为应变, stress 为应力, vonmises 为应变能强度理论下得到的等效应力值。

```

{"node":[1,2,3,6],"number":100,"strain":[-
0.0007568092860647269,0.0,0.0,0.001382484880916354,0.0,0.0010973875822819085]
,"stress":[-1.0187817312409784,-0.4366207419604193,-
0.4366207419604193,0.5317249541985977,0.0,0.4220721470315032],"vonmises":1.31
20748416504198},{ "node":[1,0,3,5],"number":101,"strain":[-
0.0001728746495571639,0.0,0.0,0.0011500736965735674,0.0,0.0013426547139789122
],"stress":[-0.23271587440387442,-0.0997353747445176,-

```

0.0997353747445176,0.44233603714367975,0.0,0.5164056592226585], "vonmises":1.1851969191611753}, {"node": [1, 3, 5, 6], "number": 102, "strain": [-0.0001728746495571639, 0.00023241118434278655, -0.00024526713169700375, 0.0005661390600660044, -1.2855947354217193e-05, 0.0007587200774713492], "stress": [-0.2401327671082305, 0.07162556666096215, -0.2958192918311842, 0.21774579233307859, -0.004944595136237382, 0.29181541441205733], "vonmises": 0.7179392254475273}, {"node": [3, 4, 6, 7], "number": 103, "strain": [-0.0004022388721066498, -0.0005087603096761036, 0.0011684578409258495, 0.0015366747766343805, 0.0006207106603416503, 0.000685780033253369], "stress": [-0.1608806751917905, -0.2428202425529088, 1.0473475656024396, 0.5910287602439924, 0.23873486936217317, 0.26376155125129574], "vonmises": 1.7300779582106856}, {"node": [0, 3, 4, 5], "number": 104, "strain": [0.0007620899968209236, 0.000632260486221794, 0.0, -0.00041715143602631406, 0.0006610036527238193, 0.0006816510612550929], "stress": [1.3906560454638166, 1.2907871911567939, 0.804432970986183, -0.16044286001012079, 0.25423217412454585, 0.26217348509811267], "vonmises": 0.8788733652948059}, {"node": [3, 4, 5, 6], "number": 105, "strain": [0.00017815536031336057, 0.000632260486221794, -0.00024526713169700375, -0.0001847402516835274, 0.0008934148370666058, -0.00014755070694947399], "stress": [0.46308992033997964, 0.8124015556541592, 0.13738031110123794, -0.07105394295520284, 0.34362109117946377, -0.05675027190364384], "vonmises": 0.8490663435674505}, {"node": [5, 6, 7, 10], "number": 106, "strain": [0.0007368315660189253, -0.0005087603096761036, -0.00024526713169700375, 6.95727936864338e-05, -0.0005203101355562474, 0.00010911202644047976], "stress": [0.5568728150025297, -0.4012747816859539, -0.19858772170203098, 0.026758766802474535, -0.20011928290624897, 0.041966164015569137], "vonmises": 0.9447219144610967}, {"node": [5, 4, 7, 9], "number": 107, "strain": [0.0013630057140168004, 0.000632260486221794, 0.0011684578409258495, -0.0009463465992533139, 0.0020344356329645035, -0.0004855629644929826], "stress": [2.8736913422231787, 2.3115796285347123, 2.7240391321532167, -0.36397946125127456, 0.7824752434478859, -0.18675498634345483], "vonmises": 1.6103173729492377}, {"node": [5, 7, 9, 10], "number": 108, "strain": [0.0013630057140168004, -7.323514915636635e-05, -0.00023098637318355207, -0.0009921265148311784, -7.05042165230587e-05, -0.0005313428800708471], "stress": [1.6593029675188165, 0.5545023035394576, 0.43315520813393016, -0.38158712108891474, -0.027117006355022573, -0.20436264618109504], "vonmises": 1.390574859104951}, {"node": [7, 8, 10, 11], "number": 109, "strain": [0.0006124384920140227, -0.0007910730714540653, 0.0003111100927091757, 0.000476278629469298, -0.00012637816914039604, 0.0007860217088708874], "stress": [0.5475347130506711, -0.5320895665401658, 0.31574363666232724, 0.1831840882574223, -0.04860698813092155, 0.3023160418734182], "vonmises": 1.1623297855142354}, {"node": [4, 7, 8, 9], "number": 110, "strain": [0.0001336708565700109, -5.4129986151544955e-05, 0.0011684578409258495, 0.0009693787305668144, 0.0003842708468279718, 0.0011646018216435496], "stress": [0.8228229923678825, 0.6783608056589934, 1.6188129803339122, 0.37283797329492857, 0.14779647954921993, 0.44792377755521134], "vonmises": 1.3615883486510383}, {"node": [7, 8, 9, 10], "number": 111, "strain": [8.78909409921462e-05, -5.4129986151544955e-05, -0.00023098637318355207, 0.00026388309518865396, -0.00032122478855018907, -0.00028062230804371674], "stress": [-0.046175479050051454, -0.15542234608366, -0.29146572072366544, 0.10149349814948229, -0.12354799559622655, -0.10793165693989104], "vonmises": 0.3961664171241216}],

"nodes": [

每一个节点的位置、序号、以及位移。

```
{
  "displace": [0.0, 0.0, 0.0], "nodenum": 0, "position": [0.0, 0.0, 0.0]}, {"displace": [0.0, 0.0, 0.0], "nodenum": 1, "position": [0.0, 3.0, 0.0]}, {"displace": [0.0, 0.0, 0.0], "nodenum": 2, "position": [0.0, 3.0, 3.0]}, {"displace": [0.0, 0.0, 0.0], "nodenum": 3, "position": [0.0, 0.0, 3.0]}, {"displace": [0.002286269990462771, 0.0015534396310553204, 0.002044953183765279], "nodenum": 4, "position": [3.0, 0.0, 0.0]}, {"displace": [-0.0005186239486714917, 0.0034502210897207025, 0.004027964141936737], "nodenum": 5, "position": [3.0, 3.0, 0.0]}, {"displace": [-0.002270427858194181, 0.004147454642749062, 0.0032921627468457254], "nodenum": 6, "position": [3.0, 3.0, 3.0]}, {"displace": [-0.0012067166163199493, 0.005673735571777373, 0.005550326706542827], "nodenum": 7, "position": [3.0, 0.0, 3.0]}, {"displace": [0.0026872825601728036, 0.0035784651895496584, 0.009031745255478648], "nodenum": 8, "position": [6.0, 0.0, 0.0]}, {"displace": [0.00357039319337891, 0.0034160752310950235, 0.006064261855240511], "nodenum": 9, "position": [6.0, 3.0, 0.0]}, {"displace": [-5.993316013740481e-05, 0.005419884265682595, 0.005371302735689854], "nodenum": 10, "position": [6.0, 3.0, 3.0]}, {"displace": [0.0006305988597221188, 0.007793103480044791, 0.009965075533606175], "nodenum": 11, "position": [6.0, 0.0, 3.0]}]}
```

2 前处理环节

2.1 建立三维模型

通过使用 FreeCAD 建模软件，构建一个积木模型，如图 1 所示，并导出.step 文件。

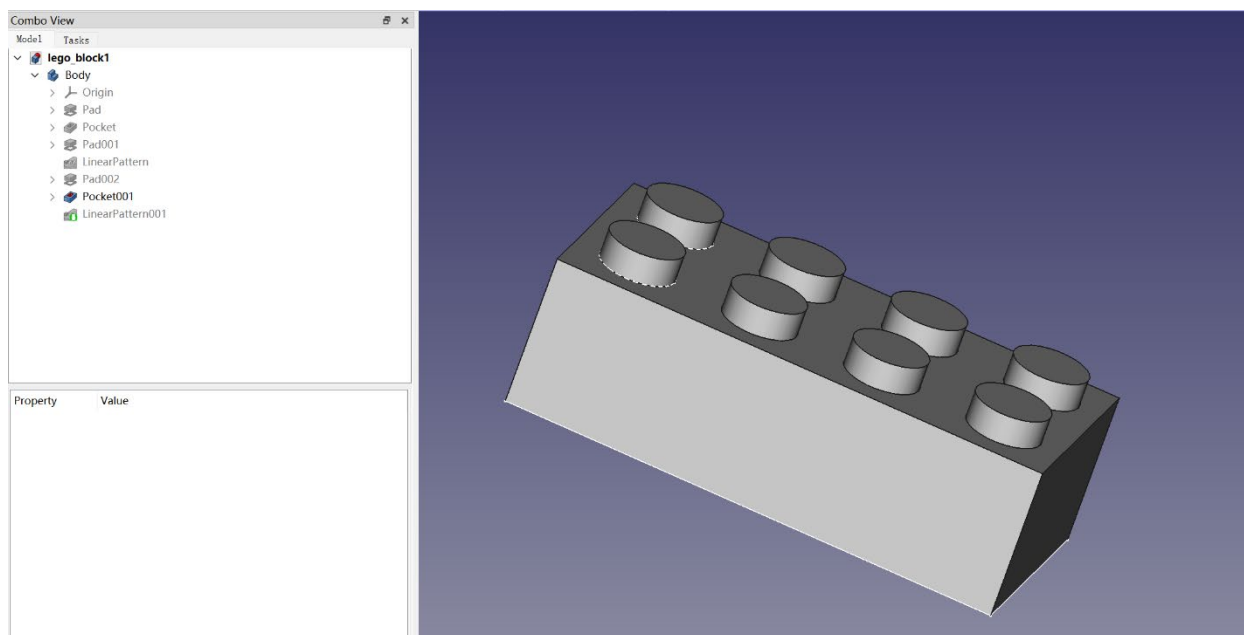


图 1 三维模型

2.2 网格划分

使用 Hypermesh 前处理软件对该模型进行处理。首先导入.step 文件模型，然后将该模型使用 tetra4 四面体网格进行自动划分。随后在模型的一侧添加位移约束，在另外一侧的 140 个节点，每一个节点添加 1N 的拉力。网格划分以及添加约束的结果如图 2 所示。

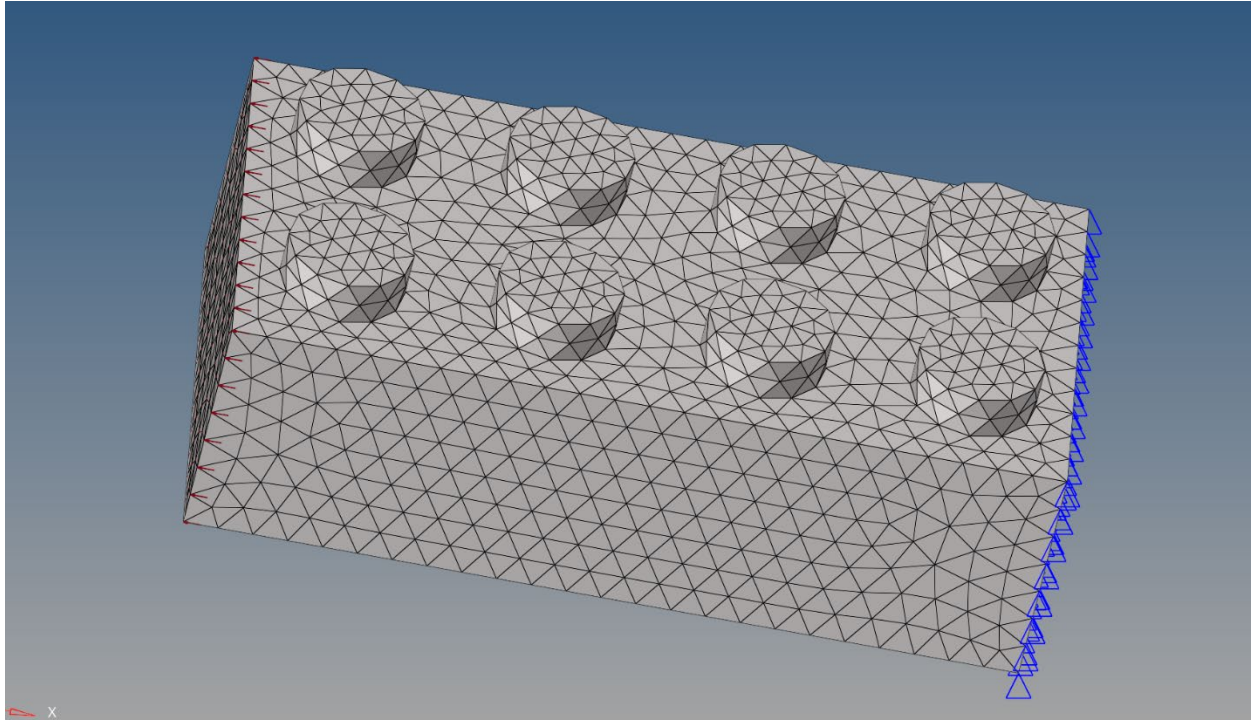


图 2 网格划分结果

将 Hypermesh 划分出的文件导出为 “.hmascii” 格式并保存，准备进行进一步处理。

2.3 输入文件格式处理

使用自制的文件格式转换程序 parsehmascii（该文件转换仅支持四节点四面体网格），将 hypermesh 导出的文件转换成 json 文件，须输入命令：

```
./parsehmascii -i block1.hmascii -o block1-in.json
```

在输出的文件 block1-in.json 文件中，添加指定材料的参数：

```
"material":{"modulus-of-elasticity":2.1e5,"poisson-ratio":0.3},
```

2.4 有限元计算

在得到输入的 json 文件之后，使用 tetra4 程序，需要输入命令：

```
./tetra4 -i block1-in.json -o block1-out.json
```

```
zqy@fedora:~/cpp_program/fem-tetra4

zqy@fedora:~/cpp_program/fem-tetra4$ ./tetra4 -i block1-in.json -o block1-out.json
Calculation finished
Nodes: 3446
Elements: 12585
Time used: 570ms
zqy@fedora:~/cpp_program/fem-tetra4$
```

图 3 程序运行结果

计算包含 3446 个节点, 12585 个单元的模型, 耗时 570ms。

在 block1-out.json 文件中, 包含了所有节点的位移量, 以及每一个单元的应力、应变、以及按照应变能理论计算得到的等效应力。

```
block1-out.json - Notepad
File Edit Format View Help
[{"elements": [{"node": [316, 313, 1439, 314], "number": 5049, "strain": [-7.6496311496082831e-07, 5.77939211252046e-06, 9.238108275679609e-07, 5.852676606185065e-06, -1.070582857402741e-05, 5.809817770820148e-06], "stress": [0.5958696294738632, 1.653834...
nises": [1.7180422991342234], "node": [1420, 1419, 31, 1438], "number": 5052, "strain": [1.1561269794474780e-06, -2.233048653759477e-06, 2.2711809922704790e-06, 3.599942373656744e-06, 4.513743488535454e-06, 1.0210...
9968, 0.1945913595367164], "volumes": [2.408644269308777], "node": [312, 313, 1437, 316], "number": 5055, "strain": [-7.2482421185439e-07, 5.566418694721986e-06, 1.8182739638340607e-06, 4.02519678087428e-06, 1.1227866084134596e-05, 5.2910061397...
0.01239293456962494, -0.009291741012921092, 0.024762278937553332], "volumes": [0.0521837112311975], "node": [1967, 1966, 1952, 2302], "number": 5058, "strain": [-3.782555195300104e-08, 5.131213094241023e-09, -0.01270654527504...
997156, 2.47752648212524, 1.183647767768218, 0.0280042200025126, -0.623408416488587, 0.024915593040980341], "volumes": [2.3628629031334666], "node": [1434, 296, 1433, 314], "number": 5061, "strain": [3.864755912527182e-06, -1.017549595618361e-05, -1.5...
871], "stress": [5072, "strain": [2.74563841609728e-06, 4.10944496190806e-06, 4.64511813783516e-06, 2.225069830321203e-06, -1.0704037800376156e-06, 1.5095976296133256e-05], "stress": [0.7127036560640408, 0.931578401738174873, -0.4826201738177487...
802809], "node": [1417, 268, 1398, 287], "number": 5075, "strain": [1.49592147768671e-06, 1.365188160400434e-06, 5.36328076376187e-07, 1.496803389576403e-06, 6.097375147149102e-06, 1.0541425011734336e-05], "stress": [0.653160281148027, 0.63240180...
41687], "volumes": [0.0200320056553325], "node": [2309, 2357, 1581, 2308], "number": 5078, "strain": [6.07031700855832e-08, 4.70764045543884e-07, 762767804004352e-08, 4.699055580950405e-07, 1.47451381802347214e-07, 5.259675678793459e-07], "s...
947295, 0.1488805161793086, 0.776603487849768], "volumes": [1.51541543174277], "node": [288, 310, 1440, 287], "number": 5081, "strain": [2.293671340829475e-06, 4.26485444814564e-06, -8.63182287119752e-07, -6.26187660227893e-06, -4.3461020536192...
-0.01604375181078808, -0.0369557533029638e-06, 0.0370191426628137, 0.04430751377035247], "volumes": [0.1490284464605622], "node": [309, 1442, 310, 287], "number": 5084, "strain": [-1.3656010822878957e-06, 7.8656337683355e-06, -5.95183251303282e-08, 1...
1, -0.00545891874026517e-06, 0.0128535619961357, 0.120677511862229, 0.0731546589784828, 0.0150540160742141e, 0.01810080687502164], "volumes": [0.1948926733213414], "node": [2290, 2316, 1972, 2291], "number": 5087, "strain": [2.046672339042976...
8210722748015e-05, -8.13508363870831e-08], "stress": [-0.309978780322901, -0.22625415436754984, -0.123257617597128, 0.5160970625609466, -1.2636170199142628, -0.006571371400495594], "volumes": [2.3740487010351616], "node": [316, 1441, 315, 1439],...
82350564139994e-06, 6.610402780406068e-06, 8.232481427615001e-06, 4.692045307319376e-06], "stress": [-0.4084850555948007, -2.59048411507103, -0.9111320475620609, 0.5393171476481824, 0.66493119223084425, 3.789728902605457], "volumes": [2.55528139...
0792819e-06, 0.841782990063586e-06, 2.390167759880526e-06, -1.753328209903835e-06, -5.93441704549365e-06, 5.754155999872285e-06], "stress": [0.652606571097095, 2.4855930959343264, 1.4434415696268099, -0.1416149707999251, -0.4791180299582833...
1892, 1959, 2248], "number": 5098, "strain": [7.246746018390388e-06, 3.30870723162364e-08, 1.02525758077388e-06, 4.37745941786109e-07, 9.08474123031104e-08, 1.081086177937394e-06], "stress": [-0.4097283876561784, -0.1061027580047732, 0.277...
8210722748015e-05, -8.13508363870831e-08], "stress": [-0.309978780322901, -0.22625415436754984, -0.123257617597128, 0.5160970625609466, -1.2636170199142628, -0.006571371400495594], "volumes": [2.3740487010351616], "node": [316, 1441, 315, 1439],...
82350564139994e-06, 6.610402780406068e-06, 8.232481427615001e-06, 4.692045307319376e-06], "stress": [-0.4084850555948007, -2.59048411507103, -0.9111320475620609, 0.5393171476481824, 0.66493119223084425, 3.789728902605457], "volumes": [2.55528139...
0792819e-06, 0.841782990063586e-06, 2.390167759880526e-06, -1.753328209903835e-06, -5.93441704549365e-06, 5.754155999872285e-06], "stress": [0.652606571097095, 2.4855930959343264, 1.4434415696268099, -0.1416149707999251, -0.4791180299582833...
1892, 1959, 2248], "number": 5098, "strain": [7.246746018390388e-06, 3.30870723162364e-08, 1.02525758077388e-06, 4.37745941786109e-07, 9.08474123031104e-08, 1.081086177937394e-06], "stress": [-0.4097283876561784, -0.1061027580047732, 0.277...
8210722748015e-05, -8.13508363870831e-08], "stress": [-0.309978780322901, -0.22625415436754984, -0.123257617597128, 0.5160970625609466, -1.2636170199142628, -0.006571371400495594], "volumes": [2.3740487010351616], "node": [316, 1441, 315, 1439],...
82350564139994e-06, 6.610402780406068e-06, 8.232481427615001e-06, 4.692045307319376e-06], "stress": [-0.4084850555948007, -2.59048411507103, -0.9111320475620609, 0.5393171476481824, 0.66493119223084425, 3.789728902605457], "volumes": [2.55528139...
0792819e-06, 0.841782990063586e-06, 2.390167759880526e-06, -1.753328209903835e-06, -5.93441704549365e-06, 5.754155999872285e-06], "stress": [0.652606571097095, 2.4855930959343264, 1.4434415696268099, -0.1416149707999251, -0.4791180299582833...
1892, 1959, 2248], "number": 5098, "strain": [7.246746018390388e-06, 3.30870723162364e-08, 1.02525758077388e-06, 4.37745941786109e-07, 9.08474123031104e-08, 1.081086177937394e-06], "stress": [-0.4097283876561784, -0.1061027580047732, 0.277...
8210722748015e-05, -8.13508363870831e-08], "stress": [-0.309978780322901, -0.22625415436754984, -0.123257617597128, 0.5160970625609466, -1.2636170199142628, -0.006571371400495594], "volumes": [2.3740487010351616], "node": [316, 1441, 315, 1439],...
82350564139994e-06, 6.610402780406068e-06, 8.232481427615001e-06, 4.692045307319376e-06], "stress": [-0.4084850555948007, -2.59048411507103, -0.9111320475620609, 0.5393171476481824, 0.66493119223084425, 3.789728902605457], "volumes": [2.55528139...
0792819e-06, 0.841782990063586e-06, 2.390167759880526e-06, -1.753328209903835e-06, -5.93441704549365e-06, 5.754155999872285e-06], "stress": [0.652606571097095, 2.4855930959343264, 1.4434415696268099, -0.1416149707999251, -0.4791180299582833...
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