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Research Article

Effect of Drinking Water Bottle Arrangement to Multi-Pack Vertical Compression Strength under Semi-Confinement Condition

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Abstract Water bottles are sold in multi-pack of several bottles and shrink-wrapped for handling purposes. When lateral pressure is applied to a multi-pack of bottles, the pack can carry more vertical stacking strength during warehousing and transportation. In this study a rubber exercise band was used to apply lateral pressure to a pack of four 16.9-oz drinking water bottles. Under this semi-confinement condition, the pack stacking strength increased up to 19% for non-interlocking bottle arrangement. However, the lateral pressure decreased the stacking strength for interlocking bottle arrangement due to the non-uniform load-carrying distribution of the four bottles. Failure occurred in the neck and shoulder areas of these bottles. Thus, adding vertical ribs or some patterns in the neck and shoulder areas would increase their compression strength.
Keywords *Water Bottles; Semi-Confinement; Bottle Arrangement*

1. Introduction

Bottled water is usually sold in multi-pack of bottles wrapped together with shrink film [1] for ease of handling. Thinner bottles have been used in recent years to minimize the environmental impact. However, thinner bottles reduce the multi-pack stacking strength during warehousing and transportation.

Confined compression strength is vertical load carrying capacity under lateral confinement. The increase of vertical load carrying capacity due to lateral confinement was well documented in concrete [2] and soil [3]. In a previous study [4], a rubber exercise band was used to apply lateral pressure to a pack of four 16.9-oz drinking water bottles. This created a semi-confinement condition for the bottles. A stiffness curve of the rubber band was developed by stretching the rubber band from 0” to 10” using a luggage scale as shown in Figures 1 and 2. The vertical compression strength of the pack increased up to some point and then decreased due to the deviation of the bottle wall from its vertical plane as the tension force in the rubber band increased (Figure 3).

The purpose of the work described in this article was to study the effect of an interlocking bottle arrangement on the vertical compression strength comparing to the non-interlocking arrangement in the previous study. Figure 4 shows a non-interlocking bottle arrangement versus interlocking arrangement.

Figure 1: *Exercise Band Stiffness Determination* [4]

Displacement (in)	Force (lb)
0.00	0.00
0.50	1.50
1.00	2.50
1.50	4.00
2.00	4.50
2.50	5.50
3.00	6.00
3.50	6.90
4.00	7.70
4.50	8.40
5.00	9.00
5.50	9.30
6.00	9.70
6.50	9.90
7.00	10.80
7.50	11.00
8.00	11.80
8.50	12.30
9.00	12.80
9.50	13.30
10.00	13.90

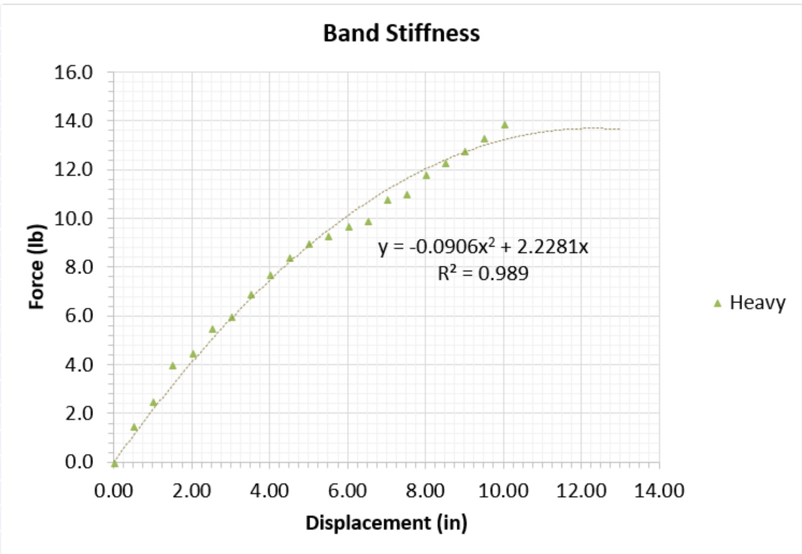

Figure 2: *Exercise Band Stiffness Curve and Equation* [4]

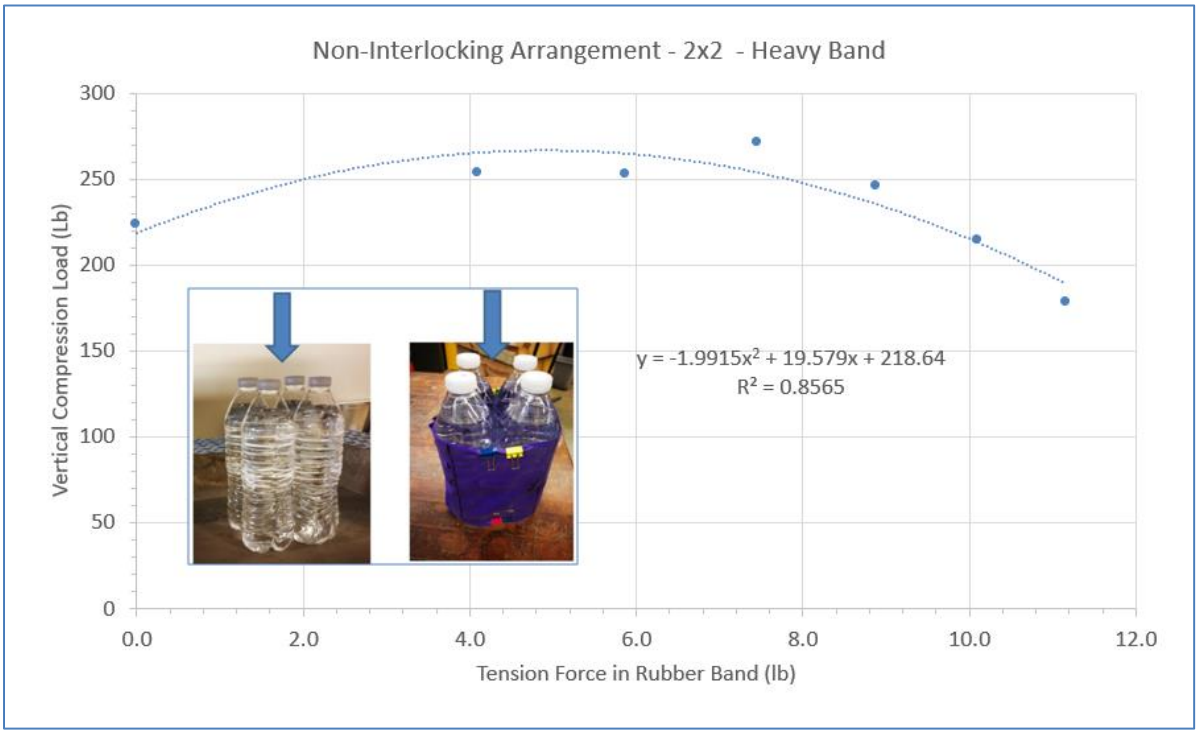

Figure 3: *Effect of Lateral Pressure on Vertical Compression Strength*

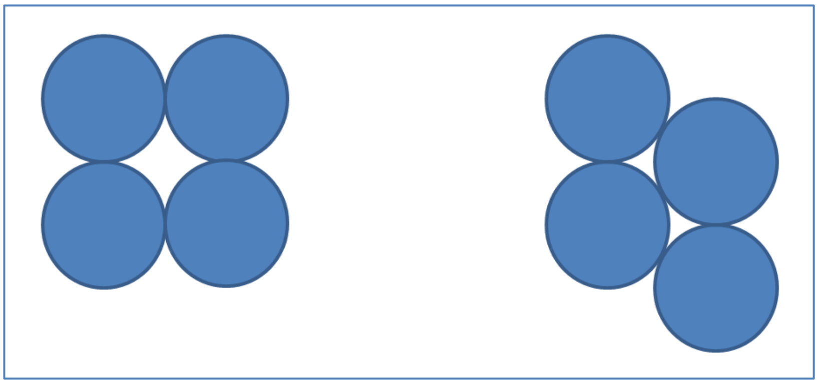

Figure 4: *Non-Interlocking Arrangement (Left) vs Interlocking Arrangement (Right)*

2. Materials and Methods

Water bottles of the same brand and size used in the previous study [4] were used in this study to maintain consistency for comparison. The same rubber band used in the previous study was also used. A non-linear stiffness curve for the rubber band was developed in the previous study which resulted in the equation shown below:

$$y = -0.0906x^2 + 2.2281x$$

where x is the rubber band stretch (in) and y is the tension force in the rubber band (lb).

The rubber band was stretched from 2 inches to 7 inches with a 1-inch increment. The above equation was used to determine the tension force in the rubber band at a specific stretch. Three sets of bottles with the same stretch were crushed by a compression table and an average maximum load was used to represent the case.

3. Data & Results

Data and results are summarized in Table 1. For comparison, data for the non-interlocking arrangement from the previous work [4] is presented in Table 2. The results of the two cases are compared in Figure 5. Trend line equations were obtained using Excel's 2nd order least squared curve fitting routine. Failures around bottle's neck and shoulder were consistent among bottles tested in this study. Failure lines were traced with black ink for visibility in Figure 6.

The peak stacking strength of the non-interlocking trend line equation shown in Figure 5 was found to be 266.76 lb at 4.92 lb of tension force in the rubber band by taking $\frac{dy}{dx} = 0$. This was about 19% increase from zero-tension case. However, the lateral pressure reduced the stacking strength in the interlocking bottle arrangement.

Table 1: *Data & Results for Interlocking Arrangement Case*

Interlocking Arrangement - 2x2 Square					
Stretch (in)	Tension Force in Band (lb)	Pmax 1 (lb)	Pmax 2 (lb)	Pmax 3 (lb)	Pmax avg (lb)
0	0.0	223	239	225	229
2	4.1	260	181	280	240
3	5.9	198	151	258	202
4	7.5	216	163	195	191
5	8.9	182	164	245	197
6	10.1	213	170	190	191
7	11.2	134	169	133	145

Table 2: *Data & Results for Non-interlocking Arrangement Case* [4]

Non-Interlocking Arrangement - 2x2 Square					
Stretch (in)	Tension Force in Band (lb)	Pmax 1 (lb)	Pmax 2 (lb)	Pmax 3 (lb)	Pmax avg (lb)
0	0.0	241	214	216	224
2	4.1	236	279	246	254
3	5.9	243	256	260	253
4	7.5	266	273	275	271
5	8.9	283	235	220	246
6	10.1	212	212	220	215
7	11.2	200	175	160	178

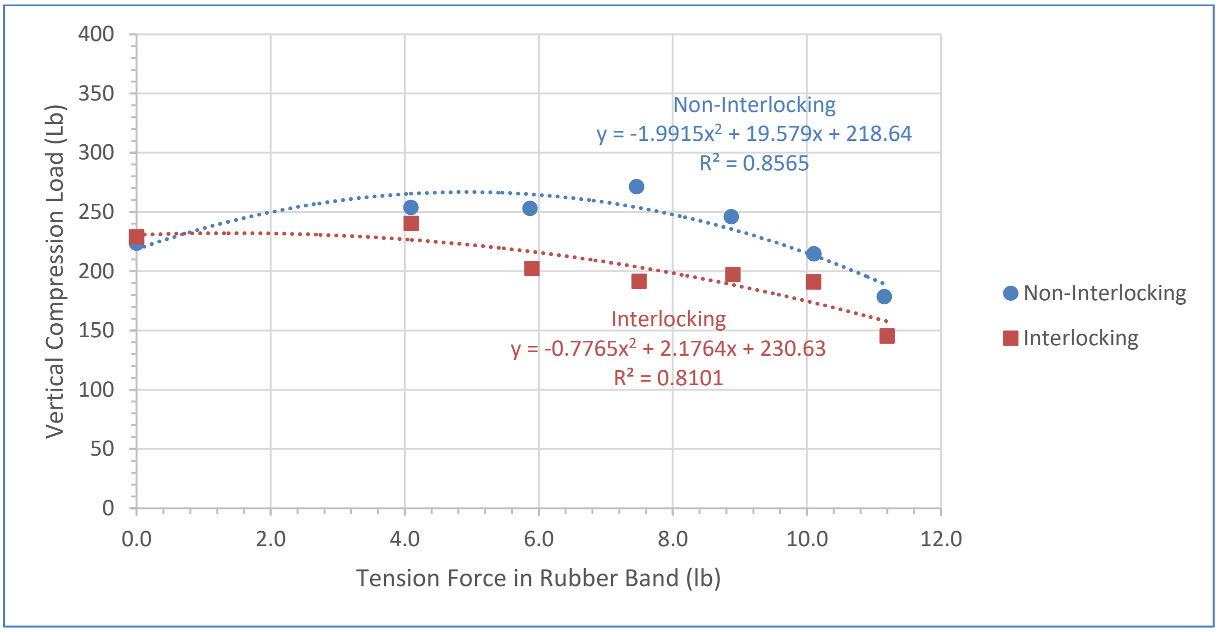

Figure 5: *Comparison of Non-Interlocking and Interlocking Bottle Arrangements*

Figure 6: *Failure on Neck and Shoulder of Bottle*

4. Discussion & Conclusion

The following observations can be made from Figure 5.

- The rise and fall of vertical compression strength of the two different arrangements follow a similar pattern with lower strength on the interlocking arrangement.
- At 0 tension force in rubber band, i.e., no rubber band, the vertical compression strengths of the two bottle arrangements are comparable.

Explanations of the above observations can be drawn from Figures 7 to 9 below. When the rubber band was tightened up, it squeezed the bottles together. Figure 7 shows lateral support provided by adjacent bottles to the lower-left bottle (which is the same as the upper-right bottle) and to the upper-left bottle (which is the same as the lower-right bottle). All bottles in the non-interlocking arrangement received the same lateral support from two adjacent bottles, thus they had a similar load carrying capacity. However, bottles in the interlocking arrangement did not receive the same lateral support. The lower-left bottle (also the upper-right bottle) received support from three adjacent bottles, while the upper-left bottle (and the lower-right bottle) received support from only two adjacent bottles. Thus, load distribution among the four bottles in interlocking arrangement was not uniform. In addition, the angle that supported the upper-left bottle from the two lateral forces from adjacent bottles in the interlocking arrangement was smaller than that of the non-interlocking arrangement. This made the upper-left bottle in the interlocking arrangement weaker than the same bottle in the non-interlocking arrangement.

Figure 8 shows resultant force from rubber band tension forces on the upper-left bottle for both arrangements. The interlocking arrangement had a larger resultant force, which caused the vertical misalignment of the upper-left bottle wall first. Due to having less angle support and more force from the rubber band made the upper-left bottle (also the bottom-right bottle) weaker than the remaining two for the interlocking arrangement

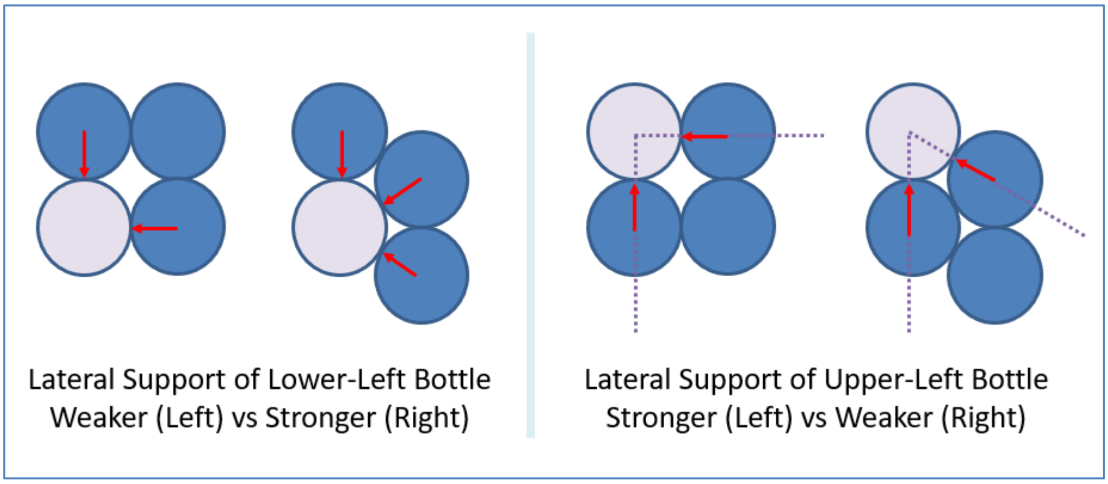

Figure 7: *Lateral Support from Adjacent Bottles*

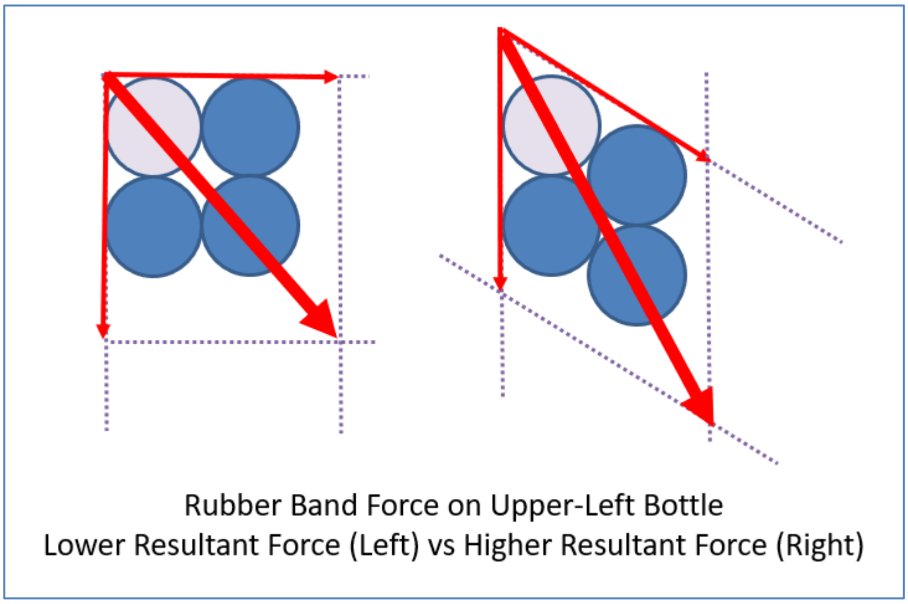

Figure 8: *Lateral Force from the Rubber Band*

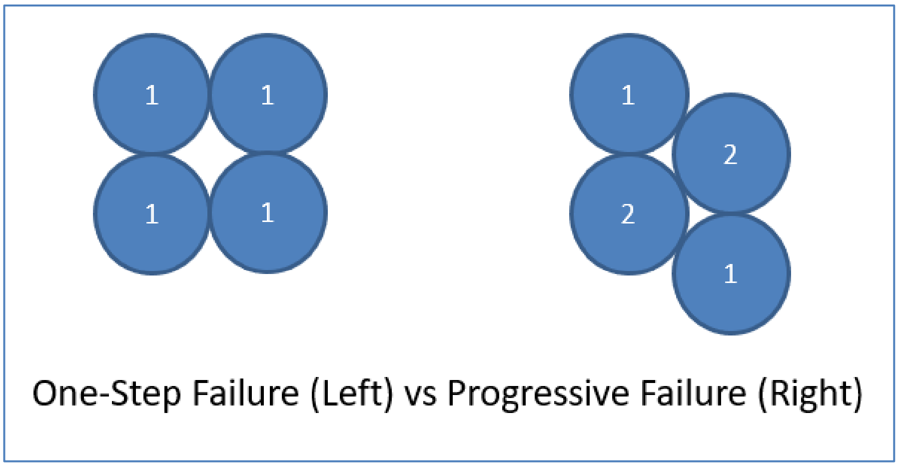

Figure 9: *Single-Step and Progressive Failures*

Figure 9 shows a single-step failure for the non-interlocking arrangement. Since all four bottles had the same load-carrying capacity, they failed at about the same time. However, in the interlocking arrangement, the upper-left and lower-right bottles (labelled "1") were weaker and failed first. Then the remaining two bottles (labelled "2") were overloaded and failed. This created a progressive failure. This explains why the interlocking curve was lower than the non-interlocking curve shown in Figure 5.

When there was no force in rubber band, the four bottles in both arrangements were not pushed against one another. Thus, each bottle behaved independently with very little lateral support from adjacent bottles. This explains the comparable compression strengths of both arrangements.

Failures, as shown in Figure 6, were around the neck and shoulder areas of these bottles. Thus, adding vertical ribs or other patterns in these areas, such as those shown in Figure 10, would strengthen the vertical compression strength.

Reference [5]

Reference [6]

Figure 10: *Samples of Patterns in the Neck & Shoulder Areas*

In conclusion, the non-interlocking arrangement gives a higher vertical load-carrying capacity than the interlocking arrangement. Interlocking arrangement is not recommended since it reduces the stacking strength of the pack. In addition, adding vertical ribs or some pattern in the neck and shoulder areas would increase the bottle's stacking strength.

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