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Prediction of Nonlinear Behaviors of Light-Frame Wood Shear Walls by Nail Connection

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ABSTRACT: In light-frame wood construction, a shear wall is an important component that provides lateral force resistance. Lateral loads acting on shear wall are transmitted to horizontal diaphragm, distrubutting the load to provide stability to the structure. Shear walls of light-frame construction consist of stud, sheathing, nails and anchorage. Therefore, the performance of a shear wall vary depending on the methods used to compose these four elements (studs, sheathing, nails and anchorage). The lateral resistance of a shear wall can be expressed as the deformation by the sum of four elements, including the effect of bending of studs, shear of sheathing, nail slip, and anchorage deformation. According to APA and CWC researches, among the four elements, the nail slip between sheathing and stud contributed approximately 65% ~ 75% of the overall deformation of shear walls. Other elements such as bending of studs, shear of sheathing, and anchorage deformation do not contribute significatly to the total racking deformation of a shear wall. In this study, the nonlinear behavior of light-frame wood shear walls resulting from nail connection between studs and sheathing among the four elements was predicted, and the results were compared with those of the shear wall deformation obtained through experimental testing.

KEYWORDS: shear wall, light-frame construction, nonlinear behavior, nail slip, cyclic load

1 INTRODUCTION

In light-frame construction, shear walls play a vital role in resisting lateral forces, which contribute to the overall stability of the structure. These lateral loads are transferred through the shear walls to horizontal diaphragms, which then distribute the loads across the building. A shear wall in a light-frame structure consists of four key components: studs, sheathing, nails, and anchorage. The overall performance of the shear wall is heavily influenced by the construction and interaction of these elements.

When lateral forces act on a shear wall, its deformation can be attributed to four primary mechanisms: stud bending, sheathing shear, nail slip, and anchorage deformation. According to Wang [1], studies by the American Plywood Association (APA) [2] and the Canadian Wood Council (CWC) [3] suggest that nail slip between the sheathing and studs accounts for approximately 65% to 75% of the total deformation in the shear wall. Given the significant impact of nail slip, much of the research has focused on predicting shear wall performance based on the shear strength of nails [4], [5]. Furthermore, researchers have explored both elastic and plastic models to better understand the behavior of shear walls under lateral loads [6], [7], [8].

However, these elastic and plastic models for shear walls can be complex and challenging to interpret due to the many variables involved in accurately characterizing shear wall deformation. As a result, this study aims to simplify the prediction of shear wall performance by focusing specifically on the nail joints between studs and sheathing panels, which account for the largest portion of shear wall deformation.

2 PREDICTION OF NONLINEAR BEHAVIORS MODELS

The proposed theoretical model is based on the following three assumptions.

1. The deformation resulting from external work is equal to the sum of the deformations caused by internal work,

2. If the force applied to the nail between the stud and the sheathing in the shear wall exceeds the yield point, the nail

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will no longer provide holding force beyond the yield load [9].

3. In the shear wall, nail positioned along the x-axis at the same height exhibit identical deformations

Based on these assumptions, the nonlinear theoretical model for shear walls is formulated as follows:

As shown in Figure 1, when a horizontal load is applied to the shear wall, the top of the wall undergoes a deformation of magnitude Δ_t. If the deformation at point y_j of the shear wall is denoted as Δ_j, then Δ_j can be expressed as shown in (1)

$$\Delta_j = \frac{\Delta_t y_j}{y_t} \quad (1)$$

Where, Δ_t: deformation at top of shear wall(mm), and Δ_j: deformation at y_j of shear wall(mm)

The deformation Δ_j, when external work(P_j) is appied to point y_j of the shear wall, is equal to the sum of the deformation of the nails along x-axis at height y_j of the shear wall. If the nails along the same axis experience equal deformaction, the deformation Δ_j can be expressed as shown in (2).

$$\Delta_j = \sum_{i=1}^{a_j} n_{s_x ij} = a_j n_{s_x i} \quad (2)$$

Where, $n_{s_x ij}$: deformation of nail at along the x-axis at point y_j (mm) and a_j: the number of nails along the x-axis at point y_j

When the deformation of the shear wall occurs in the x-axis direction, as shown in Figure 1, the deformation n_{sij} of a single nail can be expressed as shown in (3). The force p_{ij} applied to a single nail, given that the slip modulus between the framing and sheathing is k, can be expressed as shown in (4).

$$n_{s_x ij} = (y_i - y_0)\theta_j \quad (3)$$

$$p_{ij} = k \times n_{sij} = k \times (y_j - y_0)\theta_j + b \quad (4)$$

Where, p_j: the load applied a single nail in y_j(N), k : slip modulus of the nail between the nail and the framing member(N/mm) and b: Intercept of the nail between the nail and the framing member.

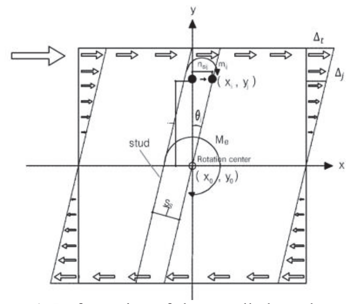

Figure 1. Deformation of shear wall along the x-axis

When the center of the shear wall is the moment center, the moment of the x-axis nails at height y_j can be expressed as shown in (5). The sum M_{xj} of the moment(m_{xij}) of the x-axis nails at point y_j, when the number of x-axis nails is a_j, is equal to (6).

$$m_{xij} = p_j \times (y_j - y_0) = \{k(y_j - y_0)\theta_j + b\}(y_j - y_0) \quad (5)$$

$$M_{xj} = \sum_{i=1}^{a_j} m_{xij} = \sum_{i=1}^{a_j} p_j \times (y_j - y_0) = a_j\{k(y_j - y_0)\theta_j + b\}(y_j - y_0) \quad (6)$$

Where. m_{xij}: Small rotational moment due to reaction force p_j of x-axis ($N \cdot m$) and M_{xj}: Total moment of x-axis ($N \cdot m$)

Similar to Fig. 1, when deformation occurs in the y-axis direction as shown in Fig. 2, the sum M_{yj} of the moment of the nail in the x-axis at height y_j is equal to (7).

$$M_{yj} = \sum_{i=1}^{a_j} m_{yij} = \sum_{i=1}^{a_j} p_j \times (x_j - x_0) = a_j\{k(x_j - x_0)\theta_j + b\}(x_j - x_0) \quad (7)$$

Where, m_{yij}: Small rotational moment due to reaction force $p_j$of y-axis ($N \cdot m$) and M_{yj}: Total moment of y-axis ($N \cdot m$)

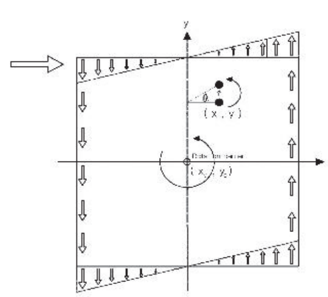

Figure 2. Deformation of shear wall alonh the y-axis

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When the moment due to external work applied to the shear wall is equal to the sum og the moments due to internal work within the shear wall, it can be expressed as shown in (8).

$$M_e = \sum_{j=1}^{t} M_{xj} + \sum_{j=1}^{t} M_{yi} = \sum_{j=1}^{t} a_j\{k(y_j - y_0)\theta_j + b\}(y_j - y_0) + \sum_{j=1}^{t} a_j\{k(x_i - x_0)\theta_i + b\}(x_i - x_0)$$

$$= \sum_{j=1}^{t} a_j\{k(Y_j - Y_0)\theta_j + b\}(y_{j-}y_0) \quad (8)$$

3 MATERIALS AND METHOD

3.1 FRAMING MATERIALS

Demension frame lumber with cross-sectional dimensions of 38 x 140 mm^2. The species of the frame lumber spine was spruce-pine-fir, and the visual grade was grade 2. When the density and moisture content of the main member were measured after the lateral load resistance test of the nail joint, the mean values were 0.42 g/cm^3 and 11.8%, respectively [10].

3.2 SHEATHING MATERIALS

. The OSB, which is a structural board with a thickness of 11.1 mm, was produced by Tolko Industries (Renton, WA, USA) and had a span rating of 24/16. The density and moisture content of OSB were 0.62 g/cm3 and 10.9%, respectively [10].

3.3 FASTENERS

The fasteners used for the joints were galvanized full round-head nails from the Senco Company (Cincinnati, OH, USA), with a diameter of 2.87 mm and a length of 64 mm. The bending yield strength of the nails was 689 Mpa [10].

3.4 SHEAR WALL SPECIMENS

Two types of specimen were prepared as shown in Fig. 3 and Table 1. The stud spacing applied to the shear wall specimens were 300mm, 406mm, and 12d nail were used to connect the framing members. the sheathing used for the shear wall was structural OSB measuring 11.1mm thick, which was attached to the frame using 8d nail. Nail spacing is 150mm on the edge and 300mm in the field of shear wall specimen

The cross section of the shea rwall specimen was 2,440mm x 2,440mm. as the sill plate, 2 x 6 $inch^2$ lumber was installed at the bottom of the specimen using anchor bolt with a diameter of 16mm at the spacing of 610mm

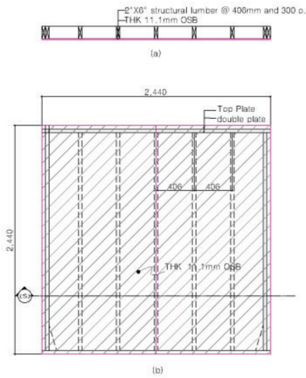

Figure 3. Schematic illustration of shear wall specimen (a) Section view of shear wall specimen, (b) Plan view of shear wall specimen

Table 1. Specification of the shear wall specimens

symbol	Stud		sheating	nail	
	Size	Spacing (mm)		Size	Spacing (mm)
OSB@ 300	2x6	300	OSB sheathing on one side	8d	150-300
OSB@ 406		406			

3.5 TESTING METHOD OF SINGLE SHEAR BETWEEN SHEATHING AND FRAME MEMBER

The nail joint was assembled using a single nail between the structural lumber and sheathing panel(OSB). The nail surface was pre-drilled with a diameter equal to 70% for the nail diameter to increase the manufacturing precision.

Four specimens were fabricated based on the orientation of the main memeber and the side member. The detail of the orientation of the main and side members for each type are provided in Table 2. Fig. 4 shows the lateral load resistance test of the nail joint using a one-sided shear test accoridng to KS F 2153 [10][11].

Table 2. Types of joint according to the directions of main and side member

type	Direction	
	Main member (Structure lumber)	Side member (OSB)
S(G)O(T)	Grain	Transverse
S(P)O(L)	Perpendicular to grain	Longitudinal

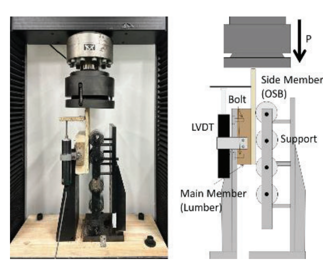

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Figure 4. Test for a single shear joint having nail with OSB side member. OSB: oreinted strand board, LVDT: linear variable-displacement transducer

3.6 CYCLIC TESTIING METHOD

Cyclic test was conducted in accordance with KS F 2154 (Korean Standard Association, 2016 [12]) and ASTM E 2126 (American Society for Testing and Materials, 2019[13]), as shown in Fig. 5. The loading block was placed on top of the specimen to deliver the lateral load uniformly via the top length of the specimen. To measure the horizontal displacement during the test, two linear variable differential transformer (LVDTs) were installed at the top of the specimen

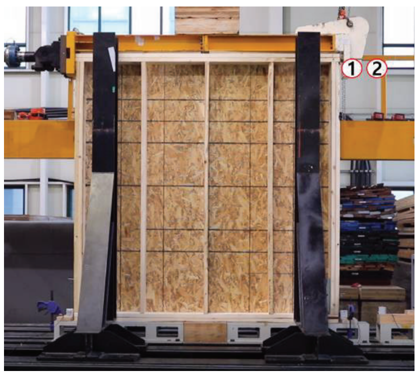

Figure 5. Test set-up for testing cyclic load of specimen

The cyclic loading schedule applied to the specimen involved quasi-static cyclic loading. The protocol procedure was consisted of a displacement-controlled loading function involving 11 loading steps. The ultimate displacement used in this study was 83.33 mm [14] as shown in Table 3. The cyclic frequency was 0.2 Hz

Table 3. Amplitudes of the Reversed Cycles

Patteran	Step	Min. Number of Cycle	Amplitude, % (Δ_m)	Displacement (mm)
1	1	1	1.25	1.04
	2	1	2.5	2.08
	3	1	5.0	4.16
	4	1	7.5	6.25
	5	1	10.0	8.33
2	6	3	2.0.	16.66
	7	3	40.0	33.33
	8	3	60.0	50.00
	9	3	80.0	66.66
	10	3	100.0	83.33
	11	3	120.0	100.00

Hysteresis curve were converted to envelope curves and Equivalent Energt Elastic-Plastic (EEEP) curve by identifying the peak point of the second loading cycles in the three loading cycles of each loading step and connecting them [14].

4 RESULTS AND DISCUSSION

4.1. SINGLE SHEAR PERFORMANCE BETWEEN SHEATHING AND FRAME MEMBER

A single shear test between the sheathing and the frame was conducted to obtain the load-displacement curve shown in Fig. 6. The first and second straight lines, as well as the yield point in Fig. 6, were determined according to the European Committee forstandardization (2005) [15]. These straight lines can be expressed using linear equations, as shown in (9). The slope, y-intercept, and yield points derived from the experimental results are presented in Table 4.

$$P = k_i\Delta + a \qquad (9)$$

Where, P : Load (kN),k :Slop of the i-th linear segment (kN/mm), i : 1,2, Δ : displacement (mm), and a : y-intercept (kN)

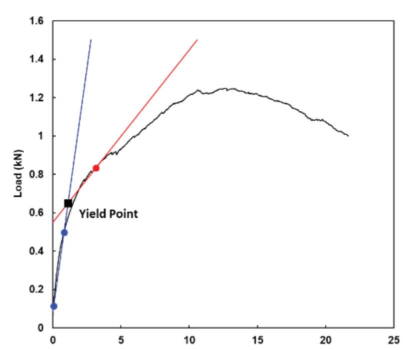

Figure 6. Load-displacement curve obtained from single shear test between sheathing and frame members.

Table 4. The slope, y-intercept, and yield point

Type	1st linear segment		2nd linear segment		Yield point	
	Slope (kN/mm)	y-intercept (kN)	Slope (kN/mm)	y-intercept (kN)	Displacement(mm)	Load (kN)
S(G)O(T)	0.505	0.119	0.086	0.732	2.209	0.862
S(P)O(T)	0.538	0.081	0.091	0.668	1.471	0.788

4.2. CYCLIC PERFORMANCE OF SHEAR WALL

4.2.1. HYSTERESIS AND ENVELOP CURVE

Fig. 7 and 8 show the hysteresis and enevelop curve resulting from the cyclic load test for OSB@300 and OSB@406 shear wall

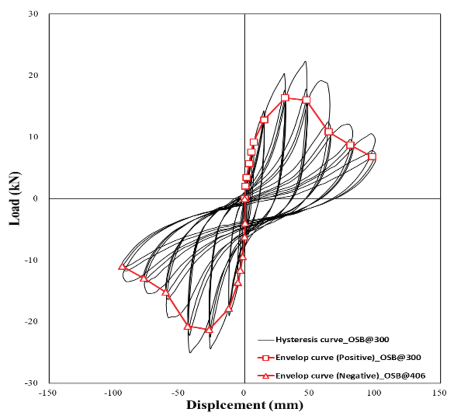

Figure 7. Load-displacmenet hysteresis and envelop curve obtained from cyclic load test for specimen OSB@300

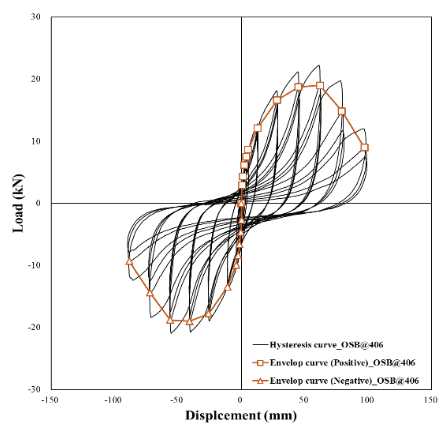

Figure 8. Load-displacmenet hysteresis and envelop curve obtained from cyclic load test for specimen OSB@406

4.3. COMPARISON WITH MODELS

In Fig. 9 and Fig. 10, the envelope curve represents both the positive and negative sides. Since the EEEP curve simultaneously accounts for both the positive and negative sides, it is represented as a single graph by averaging both sides. Additionally, as the moment induced by external forces is equal to the sum of the moments acting on the internal force, the x-axiss and y-axis of the graph are expressed as angle and moment, respectively, as shown in Fig. 9 and Fig. 10.

In this study, the sheathing and framing member were connected using nails spaced at 150 mm on the edge and 300mm in the field of the shear wall.

According to Assumation 3, nail located along the x-axis at the same height in the shear wall exhibit identical deformation. Thus, when the number of nails along the x-axis is denoted as a_j, it can be expressed as shown in (10). Therefore, applying (10) to (8) yield the result shown in (11).

$$a_j = \begin{cases} a_t \ or \ a_b : Z\left\lfloor \frac{L}{S_n} \right\rfloor + 1 \\ a_{2j-1} : the\ number\ of\ sheathing\ panel\ \times 2 \\ a_{2j} : Z\left\lfloor \frac{L}{S_S} \right\rfloor + 2 \end{cases} \quad (10)$$

Where, a_j: The number of nails between framing and sheathing along the x-axis at point y_i, a_t: The number of nails between top plate and sheathing, a_b: The number of nails between bottom plate and sheathing, S_n: The stud spacing of the shear wall (mm), and S_n: The nail spacing on the top and bottom of the shear wall (mm)

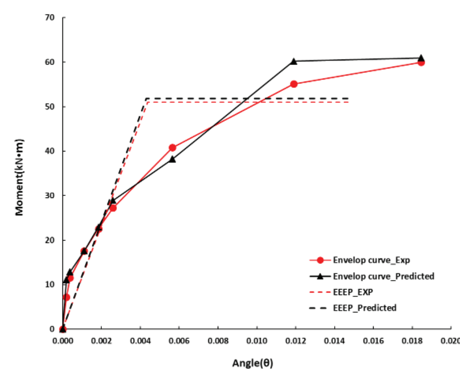

Figure 9. Comparison of envelope curve between predicted model and experimental results for OSB@300 specimen

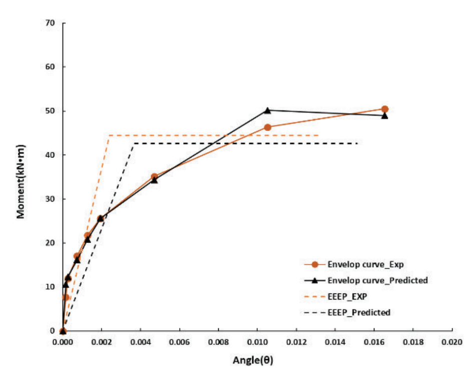

Figure 10. Comparison of envelope curve between predicted model and experimental results for OSB@406 specimen

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$$M_e = \sum_{j=1}^{t} M_{xi} + \sum_{j=1}^{t} M_{yi} = 2k(Z\left\lfloor\frac{L}{S_S}\right\rfloor + 2)\sum_{j=1}^{t-2/2}\{(Y_{2j} - Y_0)\theta_{2j+}b\}(y_{2j} - y_0) + 2k(Z\left\lfloor\frac{L}{S_{n1}}\right\rfloor + 1)\{(Y_t - Y_0)\theta_t + b\}(y_t - y_{0)} + 2k\sum_{j=1}^{t-1}\{(Y_{2j-1} - Y_0)\theta_{2j-1} + b\}(y_{2j-1} - y_0) \times (the\ number\ of\ sheathing\ \times 2) \quad (11)$$

To Compare the predicted model with the experimental results, the displacement and load value corresponding to the envelope curve obtained from the experiment were applied to the model, as shown in Fig. 9 and Fig. 10. For both OSB@300 and OSB@406, the predicted model value were similar to the experimental results in the initial stage. However, after elastic region, discrepancies between the predicted and experimental values were observed. This can be attributed to the fact that, in the initial stage, the shear strength of the shear wall is maintained by the nail. However, once the nails are subjected to forces exceeding their yield strength, they lose their holding capacity, causing the load to be redistributed to other components of the shear wall, such as the hold-down and end studs.

5 CONCLUSIONS

In light-frame timber construction, shear walls are critical structural components that provide lateral resistance. The lateral loads acting on shear walls are distributed through horizontal diaphragms, contributing to the overall stability of the structure. The deformation of shear walls is primarily governed by the deformation of the nail connections between the sheathing and the framing, which accounts for the majority of the total deformation.

In this study, a simplified prediction model was developed to evaluate the performance of shear walls based on the nail connections between the studs and sheathing panels, as these connections play a dominant role in shear wall deformation. The prediction results indicated that the model closely matched the experimental data in the initial stage; however, discrepancies emerged beyond the elastic region. This can be attributed to the fact that, in the early stages, the nails effectively sustain the shear strength of the wall. However, once the applied force exceeds the yield strength of the nails, their holding capacity is lost, leading to a redistribution of forces to other components of the shear wall, such as hold-downs and end studs.

The findings of this study demonstrate that a simplified model can be utilized to predict shear wall behavior. Future research should focus on developing more refined prediction models and conducting further experimental validation to enhance the accuracy of shear wall performance evaluations

6 REFERENCES

[1] Q. Wang. “Relationship between fastening properties and ;oad-deflection response of wood shear walls.” In: University of New Brunswick, Faculty of Fprestry and Enviornmental Management, Otawa, Library and Archives Canada.(2009).

[2] APA. “Diaphrams and shear wall.” TacomaIn, WA: APA-The enigineered wood association. (2007)

[3] CWC. “Wood design manual.” Canadian Wood Council (CWC), ottawa, canada. (2020)

[4] S,S. Jang. “Theoretical Models for predicting Racking Resistance of shear walls.” In: Journal of the Korean Wood Science and Tenchnology 30(4) (2002), pp. 96-105

[5] M. Hadi, S.Murakami, K.Komatsu. “Prediction of Nonlinear Cyclic Behaviors of Shear Wall Composed of Acacia mangium Framing and Fiber Cement Board Sheathing.” In: Journal of civil engineering 2 (2012), pp. 1-9

[6] B. Kallsner, U. Girhammar. “Plastic models for analysis of fully anchored light-frame timber shear wall.” In: Engineering structures 31 (2008), pp.2171-2181

[7] U. Girhammar, B. Kallsner. “Analysis of Influence of Imperfections on Stiffness of fully anchored light-frame timber shear wall-elastic models.” In: Material and Structures 42 (2009), pp. 321-337

[8] B. Kallsner, U. Girhammar. “Analysis of fully anchored light-frame timber shear wall-elastic model.” In: Material and Structures 42 (2009), pp. 301-320

[9] J,P. Judd. “Analysis Modeling of Wood-Frame Shear Walls and Diaphragms.” PhD thesis. Ira A. Fulton College of Engineering and Technology, Civil and Enviornmental Engineering, 2005

[10] H,W. Lee, D,B. Song, and C,K. Kim. “ Shear Properties of Nail Joint between Lumber and Oriented Strand Board (OSB) Using a Computed Method.” In: Journal of the Korean Wood Science and Technology 53(2), (2025), pp. 152-163

[11] Korean Standard Association. “Testing Method for Lateral Load Resistance of Mechnical Timber Joints.” KS F 2153. Kroean Standard Association, Seoul, Korea, 2021

[12] Korean Standard Association. “ Method of Shear (Racking) Resistance Test for Light-Frame Wood Shear Walls.” KS F 2154. Korean Standard Association, Seoul, Korea, 2022.

[13] American Society for Tesing and Method. “Standard Test Method for Cyclic Load Test for Shear Resistance of Vertical Elements If the Lateral Force Resistance System for Building.” ASTE E 2126. ASTM, West Conshohocken, PA, USA, 2019

[14] H,W. Lee, S,J. Lee, and C,K. Kim. “Lateral Resistance Performance of Hybrid Shear Wall

According to Structure Insulated Panel Installation Location.” In: Bioresources 19(4), pp. 8411-8426

https://doi.org/10.52202/080513-0666