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HURRICANE LOSS REDUCTION
FOR
HOUSING IN FLORIDA:

DEVELOPMENT OF EFFECTIVE ROOF-TO-WALL CONNECTION FOR LOW-RISE BUILDINGS TO WITHSTAND HURRICANE WIND LOADS – *PHASE 1: LITERATURE REVIEWAND CONCEPT DEVELOPMENT*

A Research Project Funded by
The State of Florida Division of Emergency Management
Through Contract # 06RC-A%-13-00-05-261

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In Partnership with:
The International Hurricane Research Center
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August 2007

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Executive Summary

Catastrophic losses due to hurricanes are the largest and most pervasive risk faced by the US coastal communities from Maine to Texas. Hurricanes of the last few years have not only cost thousands of lives and billions of dollars of damage, but most notably shredded public belief in the safety of its built environment. The growth of hurricane-induced losses from $1.3B/yr pre-1990 to $36B/yr post-2000 (National Science Board, 2007) is a direct result of over 50 years of accumulated decisions to invest in physical infrastructure and community development on the seaboard, where now 50% of the US population lives within 50 miles of the coastline (National Academy of Sciences, 1999). With losses surpassing $100B in 2005 (http://www.nws.noaa.gov/om/hazstats.shtml) and over 1,400 fatalities in 2004-05 (Govt. Accountability Office Report, 2006), hurricanes have far-reaching societal and economic impacts. As a societal need and engineering problem hurricane loss mitigation is a continuing challenge of a multidisciplinary nature.

Engineered structures are vulnerable to damage from hurricane induced wind, rain, and debris, though the combined impacts are not well understood. Damages during these extreme wind events highlight the weaknesses inherent in coastal residential building construction and underscore the need for improving their structural performance. The objective of this research is to develop a novel, cost-effective, light, strong, ductile, and non-intrusive roof-to-wall connection system using high performance fiber composite materials (as an alternative to conventional intrusive connections) through full-scale testing under simulated hurricane effects and Performance Based Design (a concept well embraced by the earthquake engineering

community). The project will assess the structural and economical feasibility, constructability, and performance of the proposed connection system through detailed experimental and analytical investigations including non-linear effects.

The current scope of work involves the (1) detailed literature review of intrusive hard ware type roof-to-wall connections – such background knowledge will be used as a baseline for the actual development of the non-intrusive roof-to-wall connection system, (2) concept development for the novel non-intrusive roof-to-wall connection, (3) formulating methodology for developing the innovative connection system.

1. Problem Statement

Minimizing the loss of life, property damage, and disruptions of economic activities from windstorms are primary objectives of wind engineering research. Extreme wind events such as hurricanes have caused substantial damage, significant economic loss, and disruption of social and commercial activities (Jones et al., 1995). The majority of residential construction performs well under gravity loads, but significant damage has been observed after major wind events such as tropical storms, cyclones, and hurricanes. Recent reports on reconnaissance of hurricane damage to structures, performed through multi-organizational efforts led by the Federal Emergency Management Agency (FEMA) and the National Institute of Standards and Technology (NIST), show that hurricane-induced losses include large numbers of damaged and destroyed residential buildings (FEMA, 2005; NIST, 2006).

In general, poor performance of a residential building (Yancey et al., 1998) has been observed when it did not respond as a unit, due to discontinuous load paths. Common practices that lead to lack of such integrity include insufficient or poorly detailed inter-component connections (e.g., roof-to-wall connections, wall-to-wall connections, wall-to-floor connections, etc).

A typical roof-to-wall connection of building structures is subjected to combined uplift and lateral loads during high wind events. The uplift is due to suction on the roofs and the lateral load components are due to in-plane and out-of-plane shear forces on the outside walls. If the roof-to-wall connections are not strong enough to transfer the uplift and lateral loads, failure may occur. Significant damage has been observed for buildings due to the failure of roof-to-wall connections (Figure 1) and secondary water infiltration occurring during hurricane wind events. Thus a roof-to-wall connection is always a critical area that needs careful design and detailing for new construction as well as retrofitting existing buildings. There is a tremendous concern for the existing stock of buildings that are not sufficiently designed to an acceptable building code.

Also, traditional intrusive connections (e.g. toe-nails, metal plates and clips connected with nails etc.) have several disadvantages as they:

- *weaken the connected structural members by intense penetrations (for example, crushing the wood fibers of the bottom chord of a roof truss by deep and dense pattern of toe-nail penetration, see Figure 1c);*
- *make the path for water infiltration through the holes created from penetrations;*
- *deteriorate rapidly in harsh environments such as coastal areas; or*
- *lack in resistance to severe wind loading such as hurricanes and tornadoes and non-linear aerodynamic loading effects (<u>failure modes: splitting and tear out of wood, nail withdrawal, nail bending, clip buckling</u>).*

Figure 1. (a to c) Typical Failures in Roof- to-Wall Connections

2. Background Literature for Roof-to-Wall Connection Testing

Relatively few experimental studies have been conducted on the inter-component connections. Studies by Rosowsky et al. (1998) and Reed et al. (1997) recognized that the behavior of inter-component connections is not well understood and recommended further testing. Past analytical studies include the different structural components as well as the inter-component connections in an assembled model. Comparisons with experimental studies were performed to assess the validity of the proposed models and analyses. To date only limited research has been directed towards the analysis of inter-component connection response for a complete building (Groom et al. 1994).

Experimental testing of roof-to-wall connections in wood frame houses (Riley and Sadek, 2003) was conducted by National Institute of Standards and Technology (NIST). The two types of roof-to-wall connections tested in this research work included toe-nailed connections and hurricane clips. The building frame specimen incorporated with these connections was subjected to four types of loading: monotonic uplift, monotonic lateral load or pushover, combined uplift and lateral load, and cyclic lateral loading. The loads were generated by vertical and horizontal actuators (Figure 2a). The experiments investigated behavior of the connections at failure. Toe-nailed connection failure mode from uplift load test was characterized with nails pulling out of the top plate of the wall, which resulted in separation in the bottom wood fibers of the bottom chord of the roof truss (Figure 2b). Hurricane clip connection failure mode from uplift load test was characterized by separation of upper member of the top plate and a portion of the lower member from the rest of the wall (Figure 2c). The behavior of both these types of connections was highly non-linear and once either of these connections reached its ultimate load it lost a significant portion of its resistance. The data obtained in these tests could provide the basis for limited analytical models of the connection response. Additional research and testing were recommended to fully quantify the response of roof-to-wall connections. The National Association of Home Builders (NAHB) Research Center, Inc., under sponsorship of the U.S. Department of Housing and Urban Development (HUD) also performed research work on roof framing connections in conventional residential construction (NAHB Research Center, 2002). Under this project, several research areas were investigated to benchmark the response of conventional and engineered roof connections. Results from the study indicate several inconsistencies in the design methodologies used for engineering analysis of traditional and hardware-type connections that can potentially lead to the development of inaccurate prescriptive connection provisions and design solutions. Testing revealed that primary failure modes for toe-nailed connections included <u>splitting and tear-out of wood</u>, <u>nail bending</u>, and <u>nail withdrawal</u>, whereas primary failure modes for joints with hurricane clips included <u>buckling of the clip</u> (Figure 2d), separation of metal truss plate, and <u>truss rotation</u>. The research report emphasized that the current design methods can potentially overestimate the resistance of certain connections and cause safety issues.

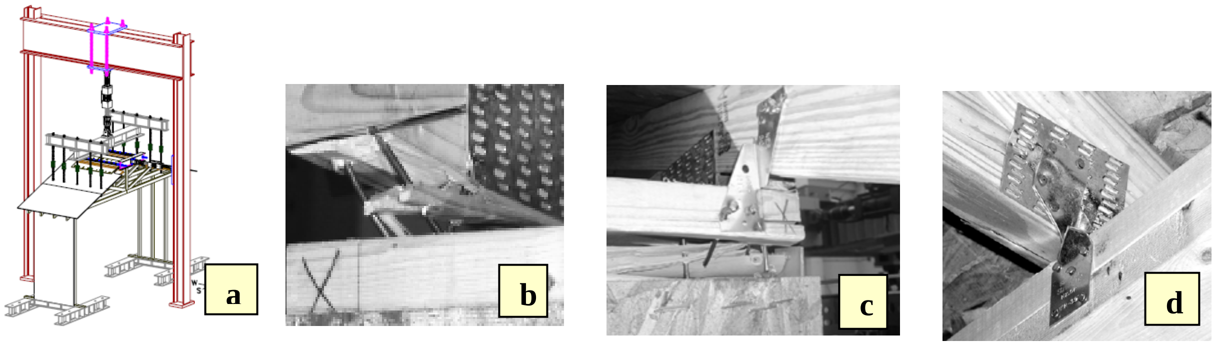
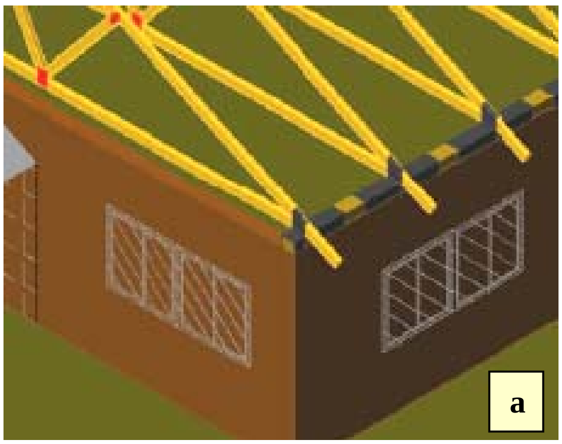


Figure 2. (a) Test Setup at NIST, (b to d) Typical Failure Modes of Roof-to-Wall Connections for NIST, NAHB

3. Proposed Concept of Non-Intrusive Roof-to-Wall Connection System

Past studies and experiments reveal that there are several inconsistencies in the design methodologies used for engineering analysis of traditional and hardware-type connections, and there are several failure modes especially during extreme wind events like hurricanes that can potentially lead to building safety issues. To circumvent these problems and to develop an efficient system that creates an effective load path from the roof through the walls, an innovative roof-to-wall connection is conceptualized. The concept is to use high performance fiber composites with high tensile strength to form a non-intrusive connection between the roof and the walls. The connection will be applicable to new construction as well as retrofitting of old residential buildings that require strengthening against hurricane wind loads with minimally intrusive techniques. The strength of the connection will be provided by the bi-directional high performance fiber composites. The efficiency of the connection system is attributed to its non-intrusiveness, thus avoiding water-infiltration problems and strength degradation issues of connecting members.

The proposed system is a durable non-intrusive fiber composite roof-to-wall connection that can be developed and installed at a cost quite comparable to existing connections. The connection will be applicable to residential houses with roof supported on roof trusses (Figure 3a) which are in turn supported on walls. Structural connections will be provided between the roof and the wall by attaching strips of high performance advanced bi-directional fiber composite sheets (with the application of high-strength adhesives) to both sides of the walls (exterior and interior) and to the members of the roof trusses. Schematic diagram for roof truss-to-wall fiber composite connection is shown in Figure 3b. The details shown are preliminary, and final design will be developed based on the proposed performance based engineering.



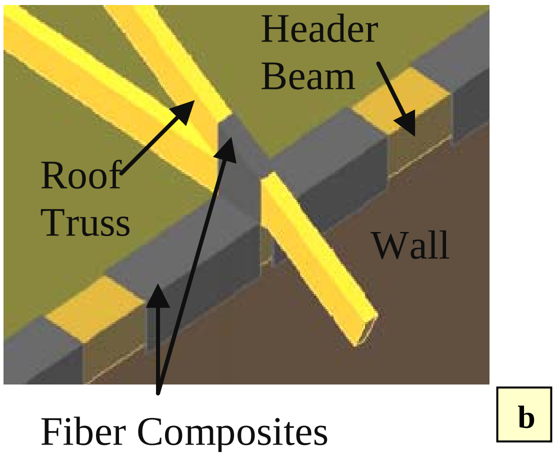


Figure 3. (a) Typical Residential Roof-to-wall Support Details, (b) Schematic for High Performance Advanced Fiber Composite Roof-to-Wall Connection

Since the fiber composite sheet is quite flexible, it can easily take the shape of the roof truss member and wrap around the roof-to-wall interfaces for almost every possible configuration of the roof and wall systems (Figure 3b). The proposed connection will provide resistance to uplift force in the case of strong hurricanes. The uplift forces on the roof will be resisted and transferred to the walls by the continuous fibers in the sheet having high tensile strength. The pull force in the sheet will be resisted by frictional force developed by the adhered surface area on the wall. The connection will also provide resistance to in-plane and out-of-plane shear forces that need to be transferred to the wall by the bond force developed in the adhered sheet surface area on both sides of the wall. In general, a continuous load path will be created between the roof and the wall for any possible loading. Areas of the composite sheets needed on the wall and the roof will depend on the expected uplift and shear forces, and could be customized for different regions (using ASCE7 Wind Load Provisions) without any deviation from the standard manufacturing operation. All connection details will be initially developed in the Structures and Construction Laboratory (CSL) at FIU using conventional actuator loads. After developing the proof-of-the-concept prototype in the laboratory conditions, the connection system will be tested under wind-rain-debris effects using the Wall of Wind.

The proposed system represents a significant enhancement in manufacturing precision, field installation productivity, structural performance and durability characteristics, when compared to the systems currently used in the construction industry (e.g., hurricane clips, toe-nail systems, etc). The proposed roof-to-wall connection system will have a number of benefits, as follows:

- The bi-directional economical, yet non-corrosive, fiber composite system will provide appropriate stiffness and strength to withstand uplift and lateral loads resulting from extreme winds such as hurricanes. Continuous load paths between roof and walls will make the building perform better as an integral system.
- Proper and durable roof-to-wall connection will prevent roof failure and associated water infiltration, saturation of dry wall, and the infestation of mold.

- The system will improve the hurricane resistance of new housing as well as old residential buildings through retrofitting using non-intrusive techniques.
- The system will be economically competitive with the traditional systems due to its reduced onsite labor and installation time.
- The system being non-intrusive will provide advantages over intrusive connections which have potential problems such as water-infiltration through holes made during intrusions and reduction in connecting member strength due to deep and intense pattern of penetrations.
- The connection will also provide insulation between the roof and the wall interface, thus increasing the energy efficiency of the building.
- Quality control is a key benefit of the proposed system with precision-made fiber composite sheets and with uniform finish.
- Durability and corrosion resistance of the fiber composite connection in harsh environments such as coastal areas makes for a durable housing system with much improved life-cycle costs.

4. Proposed Methodology for Developing the Connection System

The Phase 2 of this research will include designing, testing, and validating the innovative roof-to-wall connection by employing high performance advanced fiber composite. For such testing and validation, the research team will use the state-of-the-art newly constructed 6-fan Wall of Wind (Gan Chowdhury et al., 2007; Gan Chowdhury and Leatherman, 2007; Leatherman et al., 2007) which is currently operational at the Engineering campus of FIU. The research methodology is described in following sections.

4.1 Hurricane-Induced Wind Generation, Controls, and Calibration

The role of turbulence in aerodynamic loading was extensively documented by Li and Melbourne (1995) and others. Anemometry data from hurricanes has shown that, unlike for “straight” winds, velocity records can be *non-stationary* (Schroeder and Smith, 1998). Transient flow characteristics such as non-stationary gusts and rapid directionality changes may have significant effects on structural response (Letchford et al., 2002; Wu et al. 2001). The accuracy of the Wall of Wind testing will depend on the generation of hurricane wind effects reasonably similar to those of real hurricanes.

Using the Wall of Wind, the performance of the proposed connection system will be tested under realistic hurricane conditions including effects of non-stationary gusts, rapid directionality changes, and variations in turbulence parameters, which are often neglected in current testing practices but can have significant effects on the structural loading and corresponding responses. As a member of the Florida Coastal Monitoring Program (FCMP), the IHRC research team has invaluable high-resolution surface wind data (Masters et al., 2005) collected during many hurricanes (e.g., Isabel, Francis, Ivan). IHRC’s research team is analyzing these data to evaluate models of mean wind speed, gust factor, turbulence intensity, integral length scale, and turbulence spectra. A paper based on these analyses is currently under review for possible journal publication. A graph from this paper is given as Fig. 4a, which plots the turbulence intensity as a function of the mean wind direction for 2004 Hurricane Jeanne. Such data will be used as targets for simulating hurricane wind characteristics and calibrating the Wall of Wind flow field.

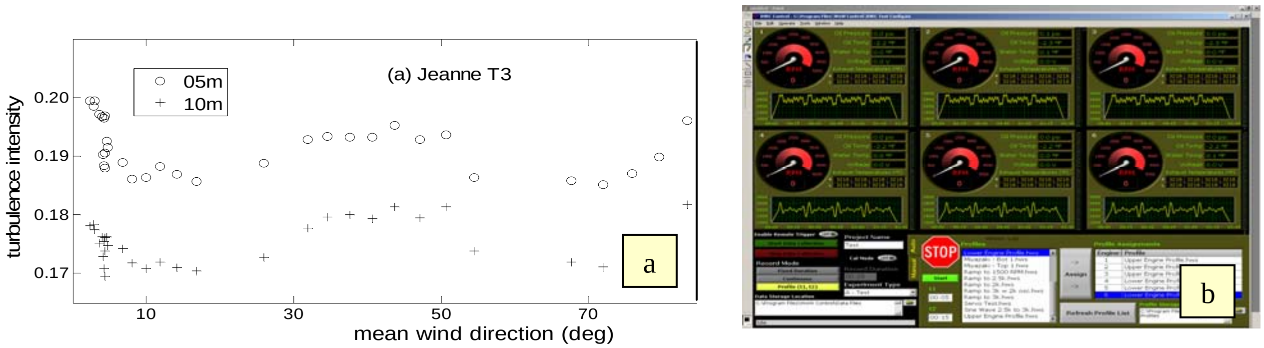


Figure 4. (a) Turbulence Intensity Analyzed for 2004 Hurricane Jeanne, (b) Gust Simulation Waveforms for Individual Fan Engines in the 6-fan Wall of Wind

Transient flow field characteristics and turbulence have been simulated actively in small scale laboratory experiments by utilizing (a) a multiple-fan array system driven by AC servomotors (each fan being individually computer controlled), and (b) oscillating vanes (Nishi et al. 1999; Ozono et al., 2006). The 6-fan Wall of Wind [2 (vertical) by 3 (horizontal) multiple-fan array system] is similar to the multiple-fan systems described above, except that the Wall of Wind is a full-scale wind simulator. Methods already proven for gust and turbulence generation for small scale experiments will be used for the generation of velocity profiles, turbulence, and gust effects for the Wall of Wind. Reasonable simulation of fluctuating and gusty hurricane wind profiles will be achieved through 1) individual servo-controlling of each fan engine for rapid variation of the fan engine speed to produce non-stationary gusts, 2) use of active control devices (oscillating bi-directional airfoils) to enhance control of longitudinal, vertical, and lateral fluctuations in the flow through multiple sinusoidal control functions assuring realistic test flow conditions. The research team will use *Arbitrary Waveform Generation* with CompactRIO and the LabVIEW FPGA Module. Based on the results of analyzing actual hurricane wind data, appropriate *gust simulation waveforms* will be used as signals to individual fan engines. For a preliminary set of such gust simulation waveforms see Fig. 4b. The robustness of the controls system will facilitate reasonable replication of hurricane conditions.

4.2 Model Building

A full-scale model representing a typical single family dwelling with wood-framed structures will be constructed for testing. The structural elements for the framing will be built using the most common current construction methods. The wooden roof trusses (with an overhang of 1 ft on each side) will be supported on the walls. Prefabricated roof trusses will have a top chord slope of 4:12. The framing for each wall will consist of double top plates, a single bottom plate (mudsill), and vertical studs. All framing and truss elements will be standard 2 x 4 lumber. The model will be provided with the high performance fiber composite system to create effective roof-to-wall connections. Windows in the building specimen will consist of *unprotected glazing* and thus simulate a *partially-enclosed condition* as they are breached by debris. This will generate the highest loads on members and connections, since that condition generates the maximum internal pressure inside a building, as prescribed by Figure 6-5 in ASCE 7-05.

4.3 Testing of the Proposed Connection System and Performance Based Design

The roof-to-wall connection employing advanced fiber composite connections will be initially developed in the Structures and Construction Laboratory (SCL) at FIU using conventional actuator loads. After developing the proof of concept in laboratory conditions, the connection system, incorporated as an integral part of the low-rise building model, will be tested under simulated hurricane wind-rain-debris effects using the Wall of Wind. Experiments will be designed to evaluate the performance of the system.

The building specimen and the connection system will be instrumented with strain gages, linear variable displacement transducers (LVDT), and pressure transducers to gain maximum information on the response characteristics of the different components. The displacement sensors will be used to measure displacements of the roof trusses and walls, and connection system deformations, and will measure both absolute and relative component motions. Vertical, lateral, and out-of-plane motions will be recorded. The pressure transducers will measure aerodynamic pressures on the roof and walls. High frequency background noise during data acquisition will be reduced by using low-pass digital filtering. Wall mounted rain gages will measure the rainfall intensities generated by the Wall of Wind. Water-infiltration at different stages will be measured by rain collecting modules mounted inside the building model. For each test the sustained mean wind speed at the eave height will be gradually increased from Category 1 to Category 4 hurricane speed. For each test, the model will be placed on the rotating turntable to allow testing for eight wind directions at 45º intervals (see ASCE 7-05 Commentary, Section C6.5.1).

Internal pressures are increased when breaches occur in the building envelope due to flying debris during an extreme wind event, thereby contributing to roof and wall failures. For the proposed research, during the debris impact test, *breach* of the windows may simulate a *partially-enclosed* building configuration (as defined in *ASCE 7-05*), for which the internal pressure coefficient is highest (GCpi=±0.55). The effect of pressurization in the building from breach of the building envelope and behavior of different connections under increasing *internal pressures* will thus be studied.

The final design for the connection system will be developed through Performance Based Engineering and Design (PBE/PBD), a well developed philosophy used by the earthquake engineering community for the design and rehabilitation of structures to ensure performance at appropriate levels in earthquakes.

PBE seeks to measure design adequacy based on multi-objective system performance rather than the traditional component strength approach. When applied to wind design, PBE can address issues of safety, serviceability, and occupant comfort for various environmental conditions. This research intends to develop the design of the innovative connection system based on multi-objective system performance, that is: 1) Performance of the system under various angles of attack and wind speed levels, 2) Performance under combined effect of wind + impinging rain, 3) Performance under combined effect of wind + rain + debris causing various internal pressures resulting from breach of the test building envelope. Based on the test results and study of the different failure modes under different testing conditions, a ***multi-objective system performance matrix*** will be evaluated. Based on the initial test results and weaknesses identified through the performance matrix, a finite element model will be developed to study and improve the connection system. Nonlinearities of the bond interfaces will be included in the analysis. Experimental pressure time histories (including non-stationary effects) will be directly applied to the finite element model to generate loading time histories. Time-dependent nonlinear analysis will be performed to obtain deformation time histories. Results of the finite element modeling will be compared to the experimental results generated from strain gages and displacement transducers. Parameters of the model (including dimensions, fiber thickness, adhesive strength, etc) will be varied to enhance the structural strength and ductility performance of the system.

After incorporation of the improvements in the connection system, the system will be experimentally re-tested under combinations of wind, rain and debris, and a new performance matrix will be generated. Such iterations using full-scale testing and numerical analysis will lead to the final design that will meet safety and serviceability requirements. The connection system will be structurally safe under hurricane wind and rain forces, efficient in eliminating water infiltration through building interfaces, durable against debris impact, and capable of resisting loads due to internal pressure increases due to building envelope breaches.

Composites have been used in the boating and aeronautical industries for over 40 years, and most concerns regarding their durability, moisture and Ultra Violet rays have been addressed using a variety of mechanisms, including gel coating.

4.4 Cost Benefit Analysis

An integral component of the proposed research is to analyze the *economic benefits* of the proposed system. This will require a detailed analysis of the various cost components as well as measures of the system's effectiveness and benefits. Cost-benefit analysis will be performed for new and existing construction. There is a strong need for a *physically-based risk model* that will allow for a scientific and accurate evaluation of the cost effectiveness of mitigation measures on the scale of a local structure, city, county, or state. The benefit and cost of the mitigation technique with the proposed connection will be evaluated by using and expanding the existing *FIU Public Hurricane Loss Projection Model* (Powell et al., 2005).

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